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An Electronic Systems Concept for the Apollo Vehicle

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FOREWORD

This report is the first of two studies being made for the Space Task Group, NASA, under Contract NAS 9-105 on Project Apollo. It covers recommendations regarding electronic radiating systems aboard the vehicle. The second report will be ready late in 1961 and will discuss the earth-based electronic environment of Apollo.

The Apollo program has the ultimate goal of landing one or more men on the moon and returning them to earth. The reader is assumed to be familiar with the general outline of this program as given in RFP 302, dated September 12, 1960, published by the Space Task Group, NASA, Langley Field, Virginia.

ACKNOWLEDGMENT

This report contains facts, suggestions and ideas obtained from many sources, particularly NASA and the Apollo Study contractors. Their contributions are gratefully acknowledged. The responsibility for the form in which these appear must, however, rest with the authors.

ABSTRACT

As a goal toward which the Apollo vehicle electronics system design should strive, an on-board system is proposed at a common frequency band, capable of voice and data transmission in both directions with a variable capability dependent on needs and the willingness to provide the payload weight to meet these needs. The same equipment elements can be used for lunar and earth altimetry, rendezvous terminal sensing against active and passive targets, tracking by the ground network, as well as approach and landing.

The near-earth orbital firings can be used to qualify increasingly sophisticated components for the lunar mission. The initial version of the communication portion of the system, after qualification with suitable ground components, will substantially exceed the capabilities of currently installed systems like Mercury.

The proposed system offers decreases in payload weight and higher reliability compared with other systems considered. These benefits come at the price of modifications of the available ground systems, integrated vehicular system design, and development effort. A system of lesser capability can be had sooner by retreating from these potential advantages.

I. The Scope of the Systems Concept

The purpose of this paper is to describe an organization of electronic equipments that will meet the electromagnetic receiving and transmitting needs of the Apollo vehicle for communications, position-finding, altimetry, rendezvous terminal guidance, approach and landing.

The functions of the system are to provide:

A. Ground-to-Vehicle Communications
   1. Voice
   2. Digital Data
   3. Transponder Interrogation

B. Vehicle-to-Ground Communications
   1. Voice
   2. Digital Data
   3. Transponder Response
   4. "Keep-Alive"
   5. Visual Information

C. Active Electromagnetic Guidance
   1. Earth Altimetry
   2. Lunar Altimetry
   3. Rendezvous Terminal Sensing
      a. Active Targets
      b. Passive Targets
   4. Approach and Landing

It has been our intention to develop a system concept which would minimize payload weight and overall system cost while maximizing reliability. Our efforts in this direction have necessarily been based largely on our experience with other electronic systems and engineering intuition since it is impossible to assess this portion quantitatively until more of the system parameters are fixed. Only enough attention has been given to detailed equipment design to assure that components of the proposed organization are within the state of the art and, in our judgment, can be procured in time to meet the Apollo schedule without a prohibitive effort.

The proposed subsystem is considered to have close and intimate design constraints with other on-board and ground subsystems. These inter-relationships will be discussed briefly to indicate where interfaces should or may be defined. The affected subsystems are:

a. the ground network
b. on-board guidance
c. on-board computation
d. structural design
e. vehicle power
f. internal capsule design
g. timing

While it is possible now to define all of the functions required of the radiating electronic systems, no attempt has been made to justify quantitative requirements (e.g., how many bits per second for telemetry?) for each function except within very broad limits, since there are no unassailable technical arguments for such requirements. The proposed system can be scaled upward or downward for different requirements.

The report is organized into the following sections:

II. The organization of a goal system is described. Combinations of the possible communication and position-finding equipments are described for such a system. Performance figures are given for one set of possible components.

III. Retreats from this goal system are considered. Recommendations are given on the utility of existing Mercury and other equipments for the Apollo mission.

IV. The compromises, advantages and difficulties of the system and equipments proposed are discussed along with frequency assignment problems.

V. A number of miscellaneous topics are considered including antennas and interaction with other subsystems.

Appendices: Details are given for communications and position-finding subsystems performance. A number of special problems are considered in detail.

Finally, there is the question of equipment multiplicity. (Shall we carry one power amplifier or two? Shall we have two directional antennas or three?) The equipment list shown in Figure 1 is a comfortable minimum. As will be demonstrated, the loss of any single unit cannot cause a loss of function although some reduction in capability must occur. More conservative reliability considerations may indicate some additional duplication of equipment, but a reduction of equipment is not recommended.

For illustrative purposes, the system parameters are calculated for transmission and reception in the neighborhood of 2.1-2.3 kilomegacycles (GC). This frequency band is chosen for illustration because

a. The 2.3 GC vehicle-to-ground band was proposed to the International Telecommunications Union for this purpose,

b. Equipment and techniques using this band are in existence or under development by the Jet Propulstion Laboratory, and

c. The frequency is near the optimum from noise considerations for lunar flight. (See Appendix D).

Actually, the bands at 1.7 and 5.4 GC (kilomegacycles) could equally well have been considered. The advantages and problems of operating at 2.1 - 2.3 GC are considered further in Section IV.

It will be evident to the specialist readers that some compromises and special designs must be made in some subsystems to accommodate multiple uses of the same equipment. Section IV will also discuss the advantages and difficulties of the proposed equipment organization.

A. Basic Equipment Lists

The on-board equipment for the Goal System is shown in Figure 1 and listed below as well, with one suggested design value shown in parentheses.

1 "Isotropic" Antenna System (see Section V)
2 Directional Antennas (26 db gain each)
1 Final Amplifier (20-watt average)
2 Driver Amplifiers (1 watt average)
2 Exciters (60 mw)

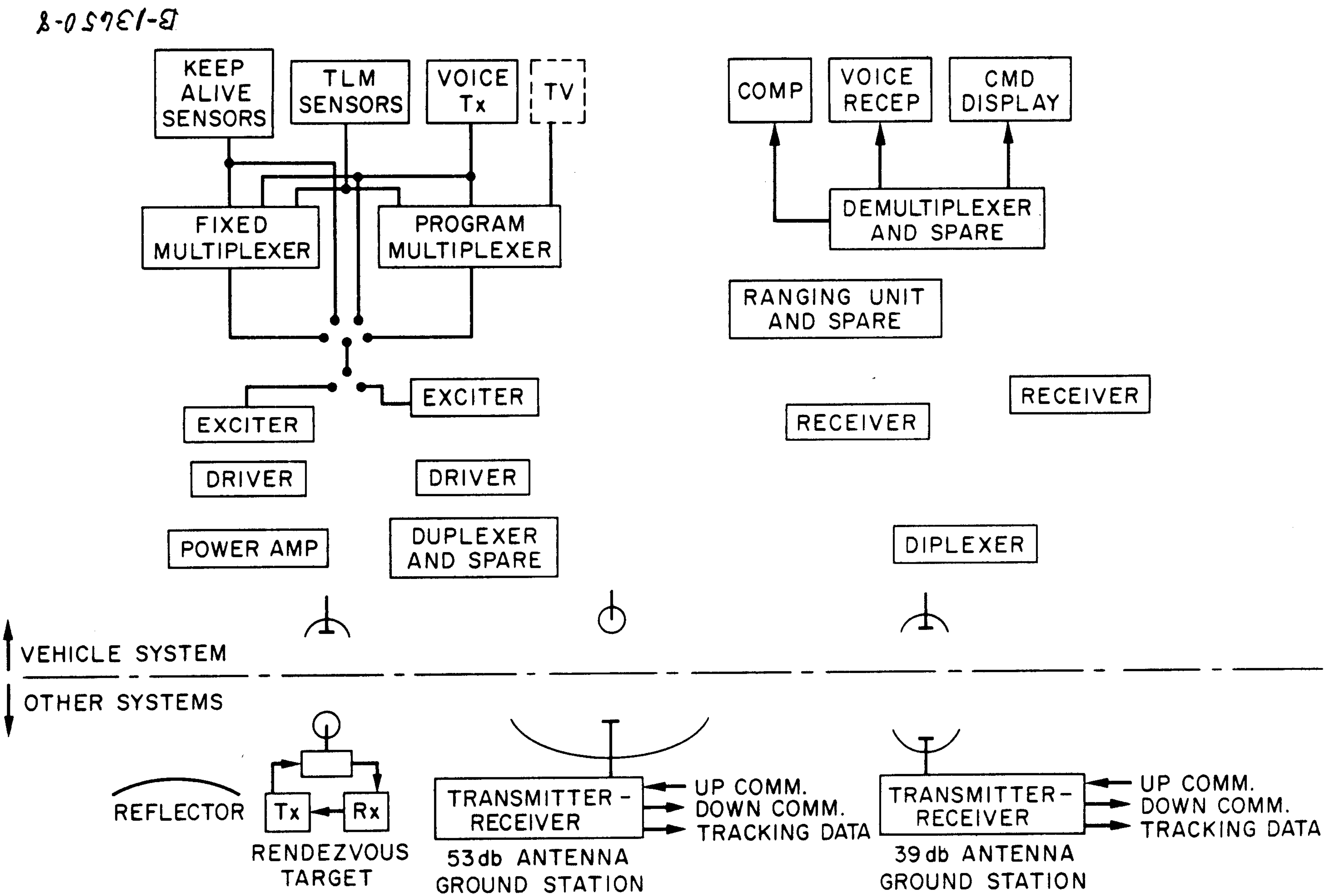

Fig. 1

APOLLO ELECTRONIC SYSTEM

2 Duplexers*

1 Diplexer

2 Receivers

2 Ranging Units (only one shown in Figure)

2 Demultiplexers (only one shown in Figure)

1 Fixed Multiplexer

1 Programmable Multiplexer (see Appendix H)

In addition to these components, the usual voice and intercommunication, telemetry sensors, computer inputs and output, and TV components are assumed to exist. One new concept is suggested: the "keep-alive" source. In the absence of any communication traffic, the system should normally drop into the "keep-alive" mode to maintain carrier phase-lock and to give some vital indication. For example, one "keep-alive" sensor might be a quantized EKG of the watch-standing astronaut.

Provision should also be made for the addition of a record output from the communication system that will be shared by the computer. This may be an electronic display or the equivalent of a teletype tape. It may be used, for example, to record long strings of ground-derived numbers before entry into the computer or to obtain intermediate computer results for diagnoses of discrepancy between ground and vehicle-computed results.

Outside the vehicle, the on-board equipment will interact with

1. <u>Passive Reflectors</u>

   These include the earth and moon for altimetry purposes and during rendezvous with silent or other satellites unequipped with the appropriate transponders.

2. <u>Active Transponders</u>

   These include suitably equipped transponding satellites for rendezvous or special ground equipment used for approach and landing.

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* A duplexer is used to time-share a transmitter and receiver on one antenna, while a diplexer is used for frequency-sharing of a single antenna by two or more equipments.

3. Ground Range Network Elements

The ground equipments significant to this discussion are principally the ground antennas. * In the era of Apollo flight there will exist the DSIF 85-foot antennas. For coverage during near-earth orbits additional ground site real estate (Mercury and/or Minitrack and/or others) is needed to assure line-of-sight communications appropriately often. These additional sites require antennas of sufficient gain to

a. minimize normal on-board vehicular power consumption and
b. relieve or back-up the DSIF for lunar missions

yet not so much as to create angular acquisition or angular rate limitation problems. Any final conclusions on (a) and (b) above must await the study of the ground system. An illustrative choice is used hereafter of a 39 db paraboloidal ground antenna at 2.3 GC (~19 feet or 6.3 meters). There is also likely to be at least one 250-foot antenna available. The possible existence of a 250-foot antenna will be ignored as a basis for system design. It may be useful to the Apollo mission in special situations.

B. Communication Combinations

Of all of the equipment combinations potentially available, the maximal set recommended is shown in Table I. ** Performance figures are shown for each of the combinations assuming the powers, antenna gains, margins and

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* A substantial difference in receiver noise temperature can be expected between the DSIF receiver sites (masers) and other stations (parametric amplifiers recommended). Unfortunately, at the terminal phase of lunar flight where the range places the largest demands on the communication system, the temperature of the antenna and front end of the best receivers are largely dominated by the lunar temperature (Appendix D discusses this point more completely) and small advantage accrues to the sites having very low receiver noise temperatures.

** There are at least 12 combinations of equipment having potentially different performance. Appendix A tells why these are limited to 5 combinations of different performance and discusses the assumptions going into the performance calculations.

TABLE I

COMMUNICATION COMBINATIONS

1. The basis for the bandwidth calculations shown are given in Appendix A and include the following assumptions: carrier phase-lock operation in a 20 cps bandwidth having a 6 db carrier-to-noise power ratio, 1.5 db noise figure preamplifiers (relative to $290^{\circ}K$), 7 db margin, modest allowances for cable and other losses in vehicle and ground, 10 db signal-to-noise ratio in the signalling bandwidth, orthogonal polarization sensing and polarization combining on the ground, 0 db "half-omni" antenna, 26.5 db vehicular directional antenna, 2.3 GC.

2. The db rating of Transmission Grade is not directly interpretable as bandwidth ratio change.

3. The cross-hatched areas, 26 db, Mode A and the Near-Earth Transmission Grade, are proposed to be the normal earth and lunar operating modes.

4. Modes A, B or C identify alternate combinations of equipments having approximately the same grade of performance.

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LUNAR TRANSMISSION GRADE	0 db	13 db			26 db			39 db		52 db
+10db S/N BANDWIDTH	----	120 cps			3 kc			63 kc		1.25 Mc
MODE		A	B	C	A	B	C	A	B	
VEHICULAR ANTENNA										
ISOTROPIC	x	x	x				x			
DIRECTIONAL (26 db)				x	x	x		x	x	x
VEHICULAR POWER										
EXCITER (60 mw)				x		x				
DRIVER (1 watt)	x		x		x			x		
FINAL (20 watt)		x					x		x	x
GROUND ANTENNA										
39 db	x	x		x	x				x	
53 db			x			x	x	x		x
NEAR-EARTH TRANS. GRADE	+44 db	+57 db								
+ 10 db S/N BANDWIDTH	125 kc	2.5 Mc								

COMMUNICATION COMBINATIONS

TABLE I

ground equipment performance indicated in the table. It is again emphasized that other balances may be desirable between expected equipment performance and safety margins allowed. The final choice must be made by the vehicle equipment and system designer in cooperation with the ground system designer. The communications system performance improves in 13 db increments. Each increment of communication system performance is identified as a "transmission grade".

The functional utility of each mode of operation is shown in Table II. As a reference for telemetry performance, it may be noted that the Mercury telemetry used an information bandwidth of about 240 cycles at high signal-to-noise ratio, exclusive of guard bands. This can be compared with the proposed 120-cycle bandwidth of the "keep-alive" mode at 10 db signal-to-noise ratio. Normal modes are shown where voice transmission is needed and where voice transmission is not in use. These are substantially the minimum vehicular power demand modes for the class of service indicated assuming that all equipment is functioning.

It is apparent that the higher transmission grades can be used at the lower bandwidths to give improved performance margins where unexpected conditions intervene. For each 13 db increase in desired margin, one grade of service should be eliminated at the highest grade and all others moved upward by one.

Provision is made for a full complement of communication services including data transmission to and from the vehicle. Whether the auxiliary equipment is actually carried in every mission or not, is unimportant. It is important that the capability for adding these services for more mature missions be available in the same basic equipment upon which a reliability history is being built.

In Figure 2 the normal mode of voice operation is shown in simultaneous use with active altimetry.

Consideration was given to the control of the switching between modes by ground command. This was rejected because there is a reasonable probability of locking the system into a non-communicating position (e. g., directional antenna not pointing at the earth with the receiver in a wide open bandwidth), and because of the added complexity of gear (e. g., ground controllable antenna pointing, remotely controllable switches, etc.) that would not normally be

TABLE II

LEGEND

This chart indicates the compatibility of various communication modes with position-finding functions from the vehicle. These functions are radar ranging (e. g., altimetry and rendezvous ranging) <u>or</u> transponder ranging.

If the final amplifier is in use for communications, it is not available for radar ranging with the consequent loss of half of the potential range. The "YES" indicates the simultaneous availability of communications and either full radar range or transponder range.

In addition to these internal position-finding functions, the ground can measure range and range rate of the vehicle as long as the communications link is operating.

B-13650-G

LUNAR COMMUNICATIONS TRANSMISSION GRADE	0db	+13 db			+26 db			+39 db		+52 db
BANDWIDTH AT 10db S/N	-----	120 CPS			3 KC			63 KC		1.25 MC
MODE		A	B	C	A	B	C	A	B	
POSITION-FINDING FUNCTIONS RADAR	YES	R/2	YES	YES	YES	YES	R/2	YES	R/2	R/2
OR TRANSPONDER	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
NEAR-EARTH COMMUNICATIONS TRANSMISSION GRADE	+44db	+57db								
BANDWIDTH AT 10db S/N	125 KC	2.5 MC								

ALTIMETRY, RENDEZVOUS RANGING AND COMMUNICATIONS AVAILABLE COMBINATIONS

TABLE II

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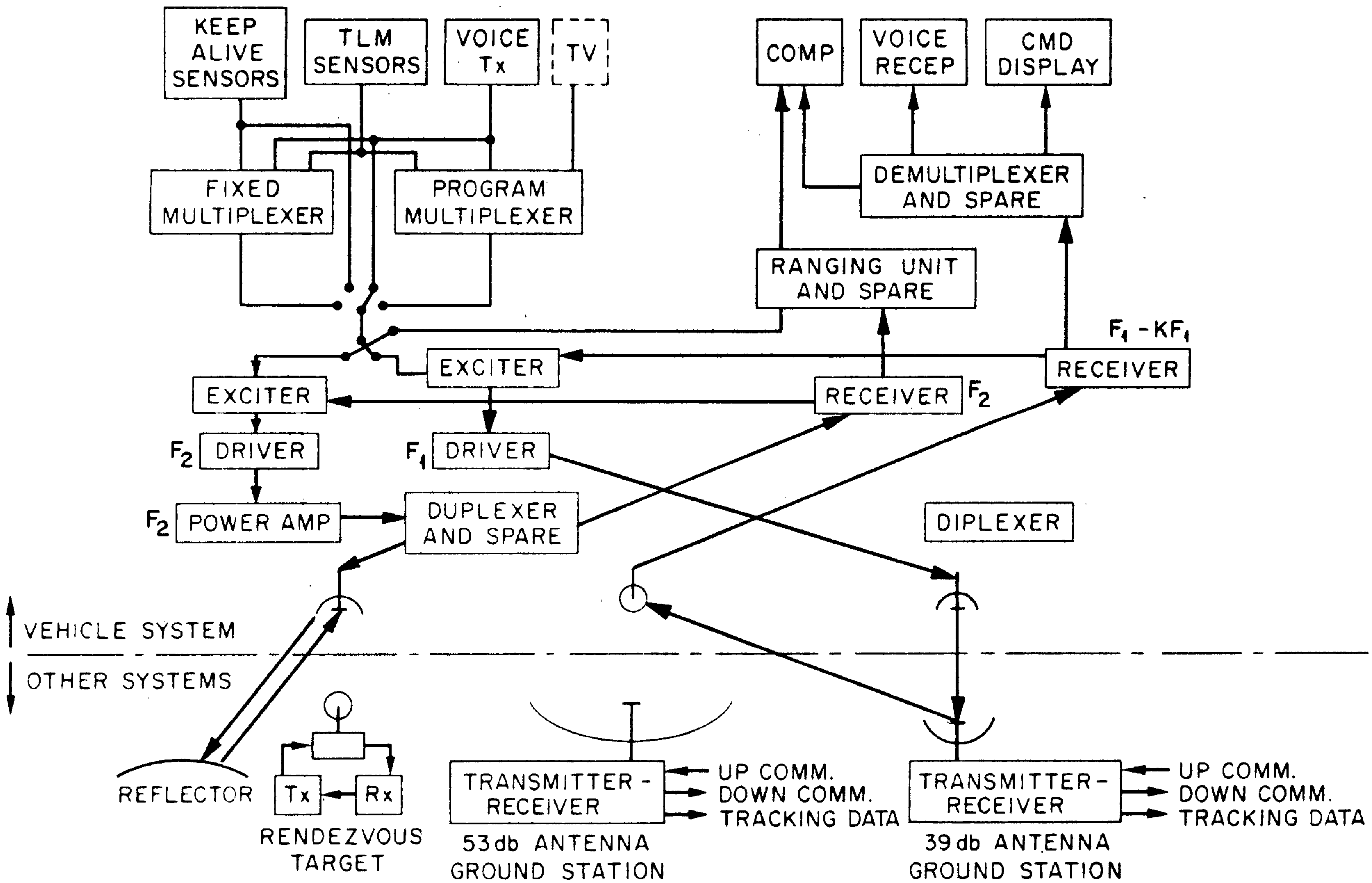

Fig. 2

APOLLO ELECTRONIC SYSTEM

POSITION - FINDING FUNCTION
RADAR

COMMUNICATION FUNCTION
NORMAL VOICE OR TELEMETRY

TRANS GRADE
26 db MODE A

carried. This implies certain restrictions on unmanned missions such as an attitude control that guarantees the "isotropic" antenna pointing to the earth and a limitation to only those communication modes that employ "isotropic" radiation. For unmanned lunar flight the number of modes employing the "isotropic" antenna is limited.

C. Position Determination, Altimetry, and Rendezvous Terminal Sensing

The system demanding the greatest radiated energy from the vehicle will probably be that required for lunar altimetry and rendezvous ranging against silent targets. At fixed frequency, the performance of these systems is largely determined by $P_T A^2$ product where P_T is the average transmitted power and A is the antenna area. Advantage is taken, in the communications system, of the existence of these components for position determination to obtain the higher grades of communication performance.

1. Altimetry and Rendezvous Ranging

Appendix G shows that 4000 km (2000 n. m.) lunar altimetry can be achieved with a system having a 1.23 meter (4-foot) diameter (26.5 db gain) antenna and less than 10 watts of average power.* Earth ranges will be substantially in excess of this because the reflectivity should be four times higher.

Appendix G discusses an unsophisticated rendezvous ranging system having better than 25 n. m. (50 km) range on 100 square meter targets using the same components. It is not proposed that angle measurement be accomplished electronically because of the added complexity and weight. (This judgment may eventually be reconsidered.) Radar angle measurement complicates the antenna by requiring either conical scan, monopulse feeds, lobe-switching, or the use of both directional antennas. Finally, the precision of radar angle measurement is an order of magnitude poorer than that of optical systems. It seems wiser to rely on optical angle measurement using current on-board optical instruments and arranging rendezvous in sunlit portions of the trajectory.

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* A simple system using a 100-watt peak power final using 100 μs pulses is actually used in the feasibility calculation. Appendix E indicates the problems and possibilities of a more sophisticated proposal for coherent altimetry, range rate measurement and ranging using a transmitter having only 10-watt peak and average power capability of a kind also suitable for communications.

2. Position-Finding by Vehicle Interrogation

For rendezvous with beacon-carrying satellites of the proper frequency, the position-finding components can be used to measure range using the same components as are used in altimetry and communications. Because of the active transponder, ranges far in excess of rendezvous ranging against inactive targets are possible. No figures are offered here because these are sensitive to the target vehicle transponder power and receiver threshold.

A more pertinent form of transponder position-finding can occur during approach and landing. Here a triplet of ground beacons can be interrogated to give range and angle to the landing site. An even simpler version is discussed in Appendix B in which interrogation is not necessary. The system is shown in Figure 3. This system will give range to the landing site as well as Left-Right steering information. No on-board equipment other than the 2.3 GC receivers and altimeter unit are needed. The unit can usefully be tied to the computer for calculating angle-off information, although this is not essential.

For water landings, similar but not necessarily identical systems can be devised for ship or island use.

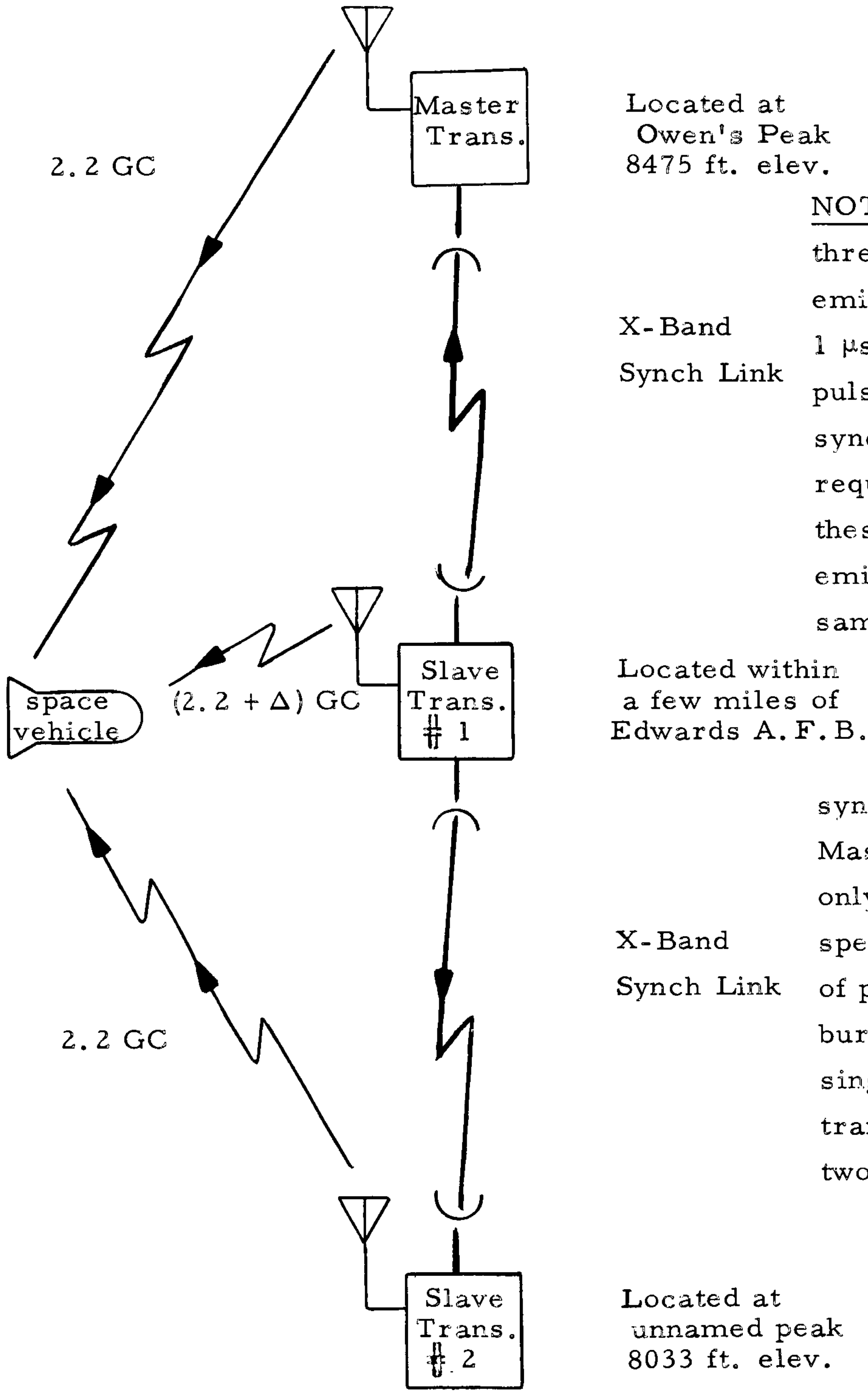
3. Vehicle Position Determination and Signal Acquisition by the Ground Network

The techniques being developed by the Jet Propulsion Laboratory are central to this proposal. The narrow band techniques are useful because they conserve vehicular power while making Doppler measurements possible at the same time. While they were developed for deep space probes, the economies are no less significant for Apollo. As in most things, some price must be paid for the gains; the price paid here is in acquisition time and some added vehicular weight which compares favorably with the weight saved in lesser power requirements. The presence of an astronaut aboard the vehicle may be useful in this system. The description of its operation will indicate its capabilities. The most demanding situation occurs in near-earth orbits because transit time across a station is sufficiently short as to place a premium on rapid acquisition of vehicular signals.

One method of acquisition is discussed below. Immediately prior to coming over the horizon of a ground station, the vehicle will radiate an unmodulated carrier at full power. The ground station must be given both angle and frequency acquisition information prior to arrival. If the 1 watt vehicle

FIG. 3

PROPOSED APPROACH SYSTEM



NOTE: Each of the three transmitters emit a sequence of 1 μs 1000-watt peak pulses. X-band synchronization is required so that all these transmitters emit pulses at the same instant. The A-scope on board the vehicle is synchronized to the Master Transmitter only because it has a special code series of pulses for each burst instead of the single pulses being transmitted from the two slave stations.

transmitter has an unlocked stability of 1 part in 10^5, the ground system will have a 17 db signal-to-noise ratio in the uncertainty bandwidth. (See the appropriate circuit quality chart in Appendix A.) Ground search need therefore be conducted only in angle until the vehicular carrier is detected. Immediately upon angle acquisition of the spacecraft carrier signal, the ground receiver is phase-locked to the received carrier. After phase-lock has been accomplished in the ground station receiver, an appropriate offset carrier is generated and transmitted to the spacecraft. The offset carrier is swept slowly in frequency so that phase-lock on this carrier can be accomplished in the vehicle. The phase-lock decision on unmanned vehicles will be based on AGC voltage or some other suitable decision mechanism. (The decision mechanism may, but need not, involve a man on the manned flights.) Once phase-lock is accomplished in the spacecraft, a suitable offset carrier is generated. (It will probably be somewhat in the frequency neighborhood of the original free-running spacecraft carrier which at this point is either switched out of the circuit or locked-in coherently to the phase-locked carrier in the vehicle.) The ground system must now phase-lock to the new space vehicle transmitted carrier. Loop phase-lock may be tested by sweeping the ground transmitter frequency in some prescribed manner. The range rate may be determined on the ground from the relationship between transmitted and received carrier. The acquisition problem near earth differs substantially from the weak signal deep-space case and rapid carrier acquisition is practical.

The best angle measurement from single pedestal antenna mounts compares unfavorably with range measurements for position determination even at 300 n. m. The next independent parameter to be measured is therefore the range. In order to measure the range, a wideband modulation must be transmitted to the vehicle and repeated back to the ground. The accuracy of such range measurement is proportional to the bandwidth of the transponded signal. The modulation of the signal across the occupied bandwidth is determined largely by convenience in making a coherent demodulation. It may be FM, coded bi-phase, or a group of sinusoidal carriers chosen to avoid ranging ambiguities.

The ground-to-vehicle path is handicapped by a poorer vehicular receiver, a wider occupied bandwidth and the need for good signal-to-noise ratio at the vehicle. This penalty may total 60-70 db. This penalty may be acceptable for near-earth orbits.

To gain added margin without a major system change (e.g., use of vehicular directional antenna in near-earth orbits, change in frequency, larger dishes or lower noise vehicular receivers), two alternatives are open. One can hold off taking a range measurement until some of the space loss is reduced; otherwise a narrowbanded vehicular receiver can be employed. The latter possibility seems to be most desirable since it will be an important, if not necessary, adjunct to lunar flight. This also permits the vehicle to have an independent measurement of range and range rate.

Therefore, the ultimate vehicular receiver should carry a range-code-following receiver (e.g., range gated system, JPL code acquisition receiver or phase-locked loops following multiple sine wave modulation). With such a narrowbanding system, the ground transmitter transmits a suitably wideband signal. This is acquired in the vehicle. The vehicular acquisition time will be dependent on the possible ambiguity or uncertainty in phase of the ground signal. Furthermore, acquisition time will depend on the signal-to-noise ratio. While studies of this problem are as yet incomplete, it seems quite reasonable that automatic vehicular acquisition can be attained in times that are even compatible with transit times across ground sites during near-earth orbits.

Upon vehicle acquisition, the wideband signal is regenerated at the vehicle and sent to the ground where a similar acquisition takes place. It is possible to devise ranging systems in which range can be measured at both vehicle <u>and</u> ground receivers, if a highly stable and known time delay is inserted at both transponders.

The ultimate in ground position measurement would be angle measurements to a degree consistent with the range measurement. Such measurements from a single pedestal seem to be beyond the state of the art. By use of wide baselines and a triplet of antennas, it appears that such angle measurements (or equivalently, triangulation through independent measurements of range and range rate at each antenna such as has been flown by Goddard Space Flight Center) are practicable. The creation of such a ground system need not place a burden on the vehicle however and will, therefore, not be discussed in this report.

D. Redundancy

Table II shows available combinations of communications and position-finding modes which are recommended for the spacecraft. The following failures cause no change in available combinations or performance:

1 Duplexer failure

1 Ranging Unit failure

1 Demultiplexer failure

The failure of the isotropic antenna requires the simultaneous transmission and reception on one directive antenna with the aid of a diplexer having a consequent insertion loss detracting from the available margin (0.5 db estimated).

If there is a multiplexer failure, the difference in multiplexers may cause, at worst, a reduction to either voice or keep-alive telemetry.

The effects of the remaining failures are shown on succeeding tables.

TABLE III

TYPE OF FAILURE

One Directional Antenna	Table IV
One Final Amplifier	Table V
One Driver Amplifier	Table VI
One Exciter	Table VII
One Receiver	Table VIII

B-13650-6

LUNAR COMMUNICATIONS TRANSMISSION GRADE	0 db	+13 db			+26 db			+39 db		+52 db
BANDWIDTH AT 10 db S/N	-----	120 CPS			3 KC			63 KC		1.25 MC
MODE		A	B	C	A	B	C	A	B	
POSITION-FINDING FUNCTIONS RADAR	YES	R/2	YES	YES	YES	YES	R/2	YES	R/2	R/2
— OR — TRANSPONDER	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
NEAR-EARTH COMMUNICATIONS TRANSMISSION GRADE	+44 db	+57 db								
BANDWIDTH AT 10 db S/N	125 KC	2.5 MC								

ALTIMETRY, RENDEZVOUS RANGING AND COMMUNICATIONS AVAILABLE COMBINATIONS

WITH ONE DIRECTIONAL ANTENNA FAILURE

The cross-hatched modes are available only on a shared-time basis between communication and position-finding.

TABLE IV

B-13650-6

LUNAR COMMUNICATIONS TRANSMISSION GRADE	0db	+13 db			+26 db			+39 db		+52 db
BANDWIDTH AT 10db S/N	-----	120 CPS			3 KC			63 KC		1.25 MC
MODE		A	B	C	A	B	C	A	B	
POSITION-FINDING FUNCTIONS RADAR	YES	R/2	YES	YES	YES	YES	R/2	YES	R/2	R/2
OR TRANSPONDER	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
NEAR-EARTH COMMUNICATIONS TRANSMISSION GRADE	+44db	+57db								
BANDWIDTH AT 10db S/N	125 KC	2.5 MC								

ALTIMETRY, RENDEZVOUS RANGING AND COMMUNICATIONS AVAILABLE COMBINATIONS

WITH ONE FINAL AMPLIFIER FAILURE

TABLE V

The cross-hatched modes are available only on a time-shared basis and then only with the range capability shown.

B-13650-6

LUNAR COMMUNICATIONS TRANSMISSION GRADE	0db	+13 db			+26 db			+39 db		+52 db
BANDWIDTH AT 10db S/N	-----	120 CPS			3 KC			63 KC		1.25 MC
MODE		A	B	C	A	B	C	A	B	
POSITION-FINDING FUNCTIONS RADAR	YES	R/2	YES	YES	YES	YES	R/2	YES	R/2	R/2
— OR — TRANSPONDER	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
NEAR-EARTH COMMUNICATIONS TRANSMISSION GRADE	+44db	+57db								
BANDWIDTH AT 10db S/N	125 KC	2.5 MC								

ALTIMETRY, RENDEZVOUS RANGING AND COMMUNICATIONS AVAILABLE COMBINATIONS

WITH ONE DRIVER-AMPLIFIER FAILURE

TABLE VI

This assumes that the final amplifier is capable of full output when driven by the exciter.

B-13650-6

LUNAR COMMUNICATIONS TRANSMISSION GRADE	0db	+13 db			+26 db			+39 db		+52 db
BANDWIDTH AT 10db S/N	-----	120 CPS			3 KC			63 KC		1.25 MC
MODE		A	B	C	A	B	C	A	B	
POSITION-FINDING FUNCTIONS RADAR	YES	R/2	YES	YES	YES	YES	R/2	YES	R/2	R/2
— OR — TRANSPONDER	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES

NEAR-EARTH COMMUNICATIONS TRANSMISSION GRADE	+44db	+57db
BANDWIDTH AT 10db S/N	125 KC	2.5 MC

ALTIMETRY, RENDEZVOUS RANGING AND COMMUNICATIONS AVAILABLE COMBINATIONS

WITH ONE EXCITER FAILURE

The cross-hatched modes are available only on a time-shared basis between communications and position-finding.

This assumes that the exciter includes certain phase-locking and ranging trigger functions not otherwise available.

TABLE VII

B-13650-6

LUNAR COMMUNICATIONS TRANSMISSION GRADE	0db	+13 db			+26 db			+39 db		+52 db
BANDWIDTH AT 10db S/N	-----	120 CPS			3 KC			63 KC		1.25 MC
MODE		A	B	C	A	B	C	A	B	
POSITION-FINDING FUNCTIONS RADAR	YES	R/2	YES	YES	YES	YES	R/2	YES	R/2	R/2
— OR — TRANSPONDER	YES	YES	YES	YES	YES	YES	YES	YES	YES	YES
NEAR-EARTH COMMUNICATIONS TRANSMISSION GRADE	+44db	+57db								
BANDWIDTH AT 10db S/N	125 KC	2.5 MC								

ALTIMETRY, RENDEZVOUS RANGING AND COMMUNICATIONS AVAILABLE COMBINATIONS

WITH ONE RECEIVER FAILURE

The cross-hatched modes are available only on a time-shared basis between communications and position-finding.

TABLE VIII

E. System Operation by Phase of Mission

This section will discuss briefly the electronic systems support during various phases of flight. This is done in most abbreviated form.

1. Launch and Injection

The system should be connected in the near-earth mode. It is assumed that angles of look are such that the vehicular "isotropic" antenna is not obscured by abort apparatus and that one antenna is chosen, from the several that will be used, that gives the best compromise coverage. During the launch and injection phase no attempt is made to measure range by transponding with the vehicular equipment because of the effects of signal dropout and because alternative measurements are being made on the booster and upper stages. Full communications and telemetry are available in the near-earth mode.

Immediately after cutoff the ground network will want full telemetry and position-finding information to monitor injection into the near-earth or parking orbit. It is, therefore, wise to run telemetry through one driver chain and range code acquisition through the other. Both drivers should feed the same antenna through the appropriate diplexer (or multicoupler).

2. Near-Earth and Parking Orbits

During routine operations both channels can continue to be operated in parallel. If higher precision ranging is desired, the final amplifier is used (+13 db Mode A) to improve signal-to-noise ratio. If, due to failure or for power economy, only one channel can be used and this can be time-shared between communications and ranging.

3. Lunar Injection

The monitoring of lunar injection requires that ground stations be near the sub-injection point. The same mode is used for lunar injection as is used during boost and launch. Here there may be a serious flame attenuation problem that cannot be directly avoided as is done during launch.

4. Lunar Transfer and Mid-Course Correction

After cutoff, communications and ranging are restored on dual channels and maintained until enough information is on hand for the first mid-course correction. Aboard the vehicle the system is switched to the directional antennas as the space loss increases and the narrowest telemetry or voice channel is time-shared (26 db Mode A) between telemetry and voice. Early transfer to the directional antenna is limited by the need for following the sub-Apollo network station across the earth as it rotates. At about 20,000 miles (40,000 km), the antenna beamwidth and reduction in apparent earth rotation rate makes transfer acceptable. After mid-course correction for power economy, the astronauts may choose to alternate between communications and ranging on a single channel.

5. Circumlunar Flight, Lunar Orbit, Lunar Landing, Lunar Take-off

At about 2,000 n.m. (4,000 km) from the moon, one directional antenna and associated gear is pointed at the moon for lunar altimetry and landing assist for those missions where landing is contemplated, while the other directional antenna is being used for communications. After landing, one directional antenna and associated driver continue to be aimed toward the earth for communication. The other driver chain may be fed into the isotropic antenna to act as a relay for local communications around the vehicle to suitable man-pack equipments.

6. Transfer to Earth and Mid-Course Correction

On the return trip the astronauts may again choose to operate dual channels in order to give the earth net as much opportunity as possible to accumulate position information up to mid-course correction. Thereafter, a time-shared operation may again be used.

7. Earth Approach and Re-Entry

Upon reaching an earth altitude of 2,000 - 3,000 n.m. (4,000 - 6,000 km) the earth altimeter is used until the time the directional antennas may be abandoned. No provision is made for communicating during re-entry while the vehicle is sheathed by plasma. At earth altitudes of 80,000 feet (approximately 25 km), the vehicle should come out of blackout and normal communications and position-finding become possible. When in line-of-sight of the impact point (300 - 400 miles), the approach system will provide range and equivalent angle information. Without vehicular aids during blackout, the ground system must be capable of tracking on the plasma sheath and wake if an independent ground knowledge of position during re-entry maneuvers is desired.

8. Recovery

This report spends little time on recovery equipment since these are largely governed by the normal equipment of the military support craft. The relatively large number of such craft (considering both the craft on station and those needed for standby and considering the possibility that craft may be called to perform an emergency recovery service from other normal duties) will be important so that the capsule recovery equipment should be electrically compatible with the normal military rescue practices and equipment. Appendix F discusses the performance of HF and UHF recovery aids.

III. Transition to the Goal System

While it is conceptually satisfying to have some ideal continually in view during the lifetime of Apollo, it is important that this goal be accessible over well-mapped technological terrain with a minimum of obstacles.

To a large extent, the route and time to get there depends on the vigor and competence of the equipment designer. It is clear that in order to obtain the advantages of the goal system, the design and development should start immediately. For reasons made clear in the next section, the system must be highly integrated. Therefore, the early design decisions must be made with the end objectives in view. The speed and ingenuity of the vehicle contractor will determine whether this system will appear in the first Apollo vehicle. One would like to have alternatives to consider.

If one wished to be conservative this development can be paralleled by the accumulation of equipment already available or under development for other applications and these used during the early flights, or in fact, for the entire Apollo lifetime. In either instance the vehicular equipment will require some additional development work. The Mercury experience shows that even existing equipment cannot be used without further work on packaging, weight reduction, cooling, etc.

This section is concerned with each of the major ground systems in which the nation and particularly NASA has a substantial investment and capability for Apollo support. The advantages and limitations of each will be briefly considered.

Two considerations weigh heavily upon any actions to be taken:

a. For the most reliable final system, the components necessary to that system should be used early and continuously in order to build up a reliability history and to uncover all "bugs".

b. If a significant capital investment must be made in an obsolescent equipment to obtain ground network coverage for a lunar mission, this should discourage its employment in favor of higher performance equipment.

A. C-Band

The most serious contender for a place aboard the Apollo vehicle is the C-band beacon. There are good arguments for its immediate use as well as potentialities for a useful existence on a lunar vehicle.

1. Immediate Advantages and Disadvantages

a. The C-band beacon has a well understood operation and limitations. By the time of the Apollo flight it will have had a substantial flight record.

b. Combined with the AN/FPS-16, it has an excellent record for accurate angular and range tracking. Both are unmatched by any other instrument of this type. The angular tracking information holds a little less interest than the range information for Apollo applications.

c. A substantial network of ground stations already exists or are already planned by the military and by NASA. The AMR will have an AN/FPQ-6 capability at four radar stations and a mobile version of the AN/FPQ-6 in South Africa. Adequate coverage at C-band will exist on the AMR for monitoring earth orbital injection. The PMR, in addition to AN/FPS-16 coverage in Australia, Hawaii, San Nicholas Island and the West Coast, will have two range ships equipped with AN/FPS-16 radars and mobile versions of this radar installed at Wake Island and on two atolls in the Marshall Island group. One can expect upgrading of PMR facilities so that C-band tracking facilities will be available in depth on both the Atlantic and Pacific Missile Ranges and in the southern portions of the USA.

d. Stations exist at:

Cape Canaveral
Ascension Islands
Kauai
Bermuda*
Eglin
Grand Turk Island
Grand Bahama Island
Woomera
Pt. Arguello
Wallops Island*
Antigua
White Sands
San Salvador

Those unmarked by asterisks are controlled by the military or foreign governments and are subject to schedule coordination whose cost is difficult to assess.

e. A C-band beacon will probably be required for range safety purposes, at least in some of the early booster stages. This opens the possibility of using a C-band beacon emplaced in the S-IV stage without necessitating that it be carried into lunar flight.

f. The problems of permitting simultaneous beacon interrogations by several ground stations are significantly less difficult (for current equipment) in the pulsed beacon than in other wideband transponders.

g. The present beacon does not now have a Doppler measurement capability but a coherent beacon is under development for use with the AN/FPQ-6.

h. The problem of isotropic antennas are marginally more difficult at C-band than they are at S-band.

i. If placed in the re-entry module it will have a slight time advantage over the S-band equipments before being attenuated by the plasma sheath.

j. It adds one more piece of equipment having a significant weight and power consumption in the vehicle. This argument is less important if the C-band beacon is used only in near-earth orbits or appears in the S-IV stage.

2. Long-Term Advantages and Disadvantages of C-Band

a. A number of C-band beacons are available or are in the latter stages of development. The AN/DPN-66 is now available and has a peak output power of greater than 500 watts, weighs less than 11 lbs., occupies a volume of less than 200 cubic inches. It requires maximum input of 45 watts of prime power. The AN/DPN-71* is a high power C-band pulse-type transponder which weighs 32 pounds and occupies 690 cubic inches. The AN/DPN-71 is scheduled for completion in October, 1961. The most recent data on this equipment is that it has a peak power of 40 kw and a maximum input power of 186 watts. In addition to the non-coherent beacons mentioned above, RCA has a coherent beacon under development for use with phase coherent trackers such as the AN/FPQ-6.

With the use of AN/FPS-16 type equipment and C-band beacons, one can expect to obtain the following standard deviations (S. D.) in measurements.

* The receiver beamwidth is 8 Mc and the triggering sensitivity is -75 dbm. A relatively few modifications in this beacon would make it suitable for Apollo.

S. D. Range 25 feet

S. D. Angle 200 microradians

The range rate measurement available from the coherent beacon is not known at this time but a reasonable design goal is for a S. D. of 1 ft/sec.

The range which can be achieved at C-band using a beacon transponder depends upon the spacecraft antenna gain characteristics. The AN/DPN-66 will allow beacon tracking to the radar horizon for the near-earth mission if the spacecraft antenna is designed to have no lobes less than 15 db down below isotropic. Beacon tracking to the limits of the range machines of the AN/FPS-16 family of radars is possible if the AN/DPN-71 is used.

b. The 40 kw beacon with the addition of a ranging unit will more than satisfy a 2000-mile lunar altimeter requirement (with 5' parabola and -100 dbm receiver). As an altimeter the short pulse (1 μs) will enable better discrimination of the nearest surface of the moon. The improvement in altimetry accuracy may not be important if the moon's surface is rugged.

c. The same equipment can be used for rendezvous ranging for silent targets.

d. By comparison with S-band the frequency increase between 2.29 and 5.4 GC give either a 7.5 db reduction in average power required for the same range or an increase of 50 per cent in range.

e. The higher-powered beacon, with directional antenna will permit ranging at lunar distances to a precision limited primarily by knowledge of the velocity of light.

f. If carried for lunar altimetry, directional antenna will have to be carried specially or the S-band antenna complicated by multiple feeds and multiple-frequency rotating joints.

3. Recommendations

a. Assuming that weight penalties are not as important in near-earth orbits as for lunar mission, the C-band beacon should be carried in the mission module for near-earth orbits.

b. No recommendation can be made regarding the relative role of the C-band beacon and the goal system for lunar missions until some value is placed on payload weight savings and some idea of delivery time for 2.3 GC goal system is obtained.

B. Use of Minitrack as a Position-Finding Aid

Minitrack exists as an operational system. It uses a minimum weight beacon which can be modified to operate in different modes depending upon mission requirements. Because of its availability, coverage, completely operational character, existing communication links to Goddard, and computer program, Minitrack represents an asset which could be used by Apollo on earth-orbital missions which have a duration of more than several orbital periods. Minitrack provides on the order of one look per orbit for spacecraft launched on either the Mercury or AMR nets for inclincation angles of 32.5°.* It provides coverage which is not otherwise available in particular regions for satellite altitudes of 100, 200 and 300 nautical miles for long duration near-earth missions.

The present Minitrack frequency of 136 Mc faces obsolescence under international agreement. However, this obsolescence probably will not take place before 1970.

The Minitrack beacon should be incorporated into the mission module. A turnstile or a slot antenna should be used with the Minitrack beacon.

The Minitrack beacon has been considered as an auxiliary aid in command module recovery. However, the limited power of the Minitrack beacon makes the use of narrowband receivers essential in the associated search aircraft. Such receivers are not generally in use and would require development for use in normal aircraft service. It is one of the premises of the recovery equipment section that recovery aids are normally found in use on existing military recovery aircraft.

Summary: Use of Minitrack in Apollo Missions

(1) Existing Minitrack stations should be used for near-earth missions for tracking.

(2) Minitrack beacon should be incorporated into near-earth mission module design.

(3) Minitrack beacon should not be used as an auxiliary aid in command module recovery.

C. Verlort Radar

The Verlort system as it is presently configured is unsuitable for the Apollo mission for at least two reasons; namely, it requires the use of an additional frequency (S-band) pulsed beacon in the vehicle with the attendant problem of antennas, and secondly the poor angular accuracy of the modified MP-61-B pedestal presently used with the radar.

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* This performance depends on reception at angles different from nominal beamwidth of the Minitrack stations. Some extrapolation of Minitrack design performance is therefore included in this statement.

There exists the possibility of modifying the system in such a way that both of the disadvantages can be removed. This would provide, without moving any radars, C-band radar coverage at four of the Mercury range sites where such coverage does not exist at the present time. These sites are the Canaries, West Australia, West Mexico, and South Texas.

The basic modification would be to replace the pedestal and antenna with a precision pedestal and suitable antenna (14-foot). The remainder of the RF system (Magnetron, Duplexer, Mixer, Local Oscillator, RF amplifier and waveguide) would have to be replaced. It is understood that such modifications have been proposed and are under consideration by owners of similar radars.

These modifications would provide a radar with angular accuracy of 0.1 to 0.2 mils and a range accuracy of about 50 feet. The ranging limit (without recycling) would be 4.6 million yards subject to adequate signal being available.

Summary:

With these modifications, the equipment becomes analogous to the FPS-16 and the conclusions therein largely apply.

D. Mercury Voice and Telemetry

The early Apollo capsule flights will be devoted to capsule system development and qualification. As such, a highly reliable and versatile telemetry and communications system with good resolution is necessary. Also, the information capacity of the system needs to be large because many measurements must be made to satisfy the various systems designers' requirements. For example, Mercury capsule development flights used two distinct channels, each with 16 subcarriers, as contrasted with the normal single channel having four subcarriers. On-board tape recorders will probably accommodate only a portion of the entire telemetry needs; they afford little use in the event of a major failure which causes complete loss of the capsule.

There are a few reasons for not relying solely on the final 2.3 GC Apollo telemetry and communications system for early R and D flights:

(1) The Apollo system will be undergoing R and D itself and will not be fully reliable. PCM equipment failures tend to be severe in that a single failure can cause complete loss of several channels.

(2) R and D telemetry requirements are greater than those for a normal mission.

(3) A complete set of ground stations capable of receiving 2.3 GC PCM telemetry would be needed early in the Apollo program to provide sufficient coverage.

A telemetry and communications system that suggests itself for R and D use is that used for Project Mercury. Some of the significant features in using the Mercury system are listed below:

(1) Mercury equipment is usable with some modifications and vehicular equipment power increase. The ground stations could be modified to increase their capability to PAM/FM/FM reception of several separate carriers at the expense of diversity reception. Additional tape recorders at each station can be used for recording post-detection data for which discriminators and decommutators are not available at the station. A limited quick-look capability is present using installed recorders and displays, although some scale changing may be necessary. These expenditures will have a very limited lifetime.

(2) Telemetry coverage is good for flights down AMR. Mercury station coverage is satisfactory for orbital flights of one to three orbits at a 300-mile altitude along the Mercury inclination plane. This coverage should suffice for R and D flights.

(3) A great deal of operational experience with Mercury equipment will exist before the first Apollo flights.

(4) Mercury equipment can be placed in the mission module, as can the antennas, and thus one avoids redesign of the command module for various phases of the project. The space in the mission module can then be utilized for other purposes on post-development flights and the VHF antennas removed or abandoned.

(5) The Mercury voice system can be used for early manned training and evaluation flights if the final 2.3 GC system is not yet fully operational, or at least as a backup for the final system in early flights. However, there is less reason to be concerned about voice transmission at 2.3 GC.

Summary:

The 2.3 GC goal system should be developed with all possible speed and ground stations installed for it as soon as possible. Partial qualification (on the ground) of this system early in the program would permit its being carried in the first R and D flights. The existing Mercury-type telemetry and voice communications equipment could also be used in early flights for reliability and to handle the extra sensor requirements. Excessive expense in modifying Mercury equipment should be avoided, incorporating changes in the goal PCM system if necessary.

E. Transition to the Goal System

The utility of the C-band equipment for Apollo depends upon a number of conditions. The distribution of the AN/FPS-16 family is mainly along the AMR and PMR facilities. For earth orbital missions it seems likely that the C-band equipment now available can provide valuable tracking information even if only a beacon of modest size is used. If the earth orbital launches are not to be over the Mercury range or AMR or PMR, the possibility of developing a new set of spacecraft equipment for Apollo exists.

For a minimum capability system with suitable restraints on launch and orbit, a C-band beacon with a Minitrack beacon backup will provide adequate ground tracking on near-earth orbital missions. This system could use Mercury-type telemetry and voice equipments that are already in place. It is, in fact, a Mercury-type system with a Minitrack tracking backup. In order to increase communications coverage to one-to-two communication contacts per orbit with either a C-band or Minitrack station on near-earth missions, a significant investment in additional Mercury communications would be necessary at these stations. The evolution of this minimum system is, therefore, limited insofar as communications is concerned. On the other hand, there is no question but that a continual upgrading of both C-band trackers and beacons will take place and a coherent C-band beacon will be available eventually. Thus, a measurement of range rate will be added to the C-band system. As the evolution of the C-band tracking facilities and equipments occur, the communications and telemetry equipment will move to S-band and the S-band equipment will probably make use of a phase lock receiver to minimize spacecraft power requirements. The existence of a phase lock system at S-band for communication opens the door to S-band ranging using a code. The S-band ranging and communication system (Goal System) appears desirable for a number of reasons.

(1) The C-band tracking facilities may not be located suitably for particular missions.

(2) The problem of liaison with the military ranges for programming flights will exist.

(3) It may be desirable to qualify S-band equipment on near-earth orbits. Although this may be done using the JPL portable system, ranging can easily be installed with the near-earth communication equipment and used in addition to or in lieu of C-band tracking.

One may conclude that a C-band beacon and an S-band communication and ranging system of the type described in Section II form a second (intermediate) system which will be useful in earth-orbital missions. Whether new facilities are built clearly depends on future plans on orbits, missions, and requirements. The possibility of a special system to monitor lunar injection also exists and it is clear that the spacecraft electronic package may be tailored to some extent to fulfill a particular mission requirement and should be flexible enough to accommodate changes as the need for changes arises.

As the Apollo mission progresses, we foresee the utility of a unified system for Apollo near-earth and lunar missions. In this case the ranging and communication would be from the Goal System for both near-earth and moon. For the near-earth case, this suggests a self-contained NASA net with a commensurate investment in facilities but has the advantage of operational control of facilities, and scheduling. As far as the spacecraft equipment is concerned in an ultimate system, goal system equipment could be used for near-earth and lunar operation with an operational hand-over between the DSIF and near-earth system based upon a predetermined standard procedure of operation.

Let us return to the minimum system and the spacecraft equipment which will be used for it. The current system would use a C-band beacon, a Minitrack beacon and a Mercury-type communication package for near-earth orbits. For lunar orbits, the goal equipment would be used for ranging and communications and a C-band beacon used for lunar altimetry. We are not considering rendezvous on the initial lunar mission. A modified communication package compatible with the Mercury ground communications receivers could be used on the 4th stage of the vehicle in the lunar mission to maintain communications during parking orbit and lunar injection.

Table IX may be viewed as a form of chronological development of an Apollo-type net. The current system is composed largely of developed equipment. The C-band beacon needs modification it it is to be used as an altimeter and a display must be added both for altimetry and the C-band landing aid. The current system requires some amount of capital investment principally in the ground network.

The intermediate system fills the existing gap in C-band coverage with a goal system for the near-earth orbits. For monitoring lunar injection, assuming that this is necessary although it is only conjecture at the moment, there are three possibilities. A coherent C-band system could be used. Such a beacon is under development. A goal-type installation is also a possibility particularly since goal-type equipment will be carried in the vehicle anyway. The Goddard vector position and velocity measuring equipment is also a strong contender but requires a special transponder. For lunar operation, altimetry, re-entry and landing, elements of the goal system are suggested to provide the required function on the vehicle.

An ultimate system makes use of a unified, simple-frequency-band concept. The range is unified and NASA operated and controlled. It requires minimum power and equipment in the vehicle.

The relative costs of the minimum, intermediate, and ultimate systems are hard to estimate. The ultimate system will certainly require an immediate ground system capital expenditure. On the other hand, the minimum system can give some limited coverage without as much immediate outlay. This difference in rate of spending must be weighed against the importance of savings in vehicular weight and power.

TABLE IX

SPACECRAFT EQUIPMENT

	Near-earth	Lunar Injection	Deep Space	Re-entry	Landing
Current System	C-band beacon Minitrack Mercury com. equipment	C-band beacon	DSIF C-band beacon for altimetry	C-band altimeter C-band beacon	Rcvr. of C-band beacon
Intermediate System	C-band beacon Goal System	Coherent C-band beacon or Goal System comm. and ranging equip. or Goddard type position and doppler system	Goal System including altimeter	Goal System	Goal System
Ultimate System	Goal System	Goal System	Goal System	Goal System	Goal System

IV. The Advantages and Difficulties of the Goal System

In recommending a system design, one would ideally establish a measure of effectiveness (such as overall system cost for pre-established system missions of given reliability on given schedules) and optimize this measure of effectiveness in an n-dimensional space whose coordinate axes are each of the design parameters (such as frequency, vehicular power, vehicular antenna size, etc.).

In real life such a total parametric study is not available. How does one weigh the importance of the U. S. position at the International Telecommunications Union on the use of 2.3 GC for space communications? How does one quantify the increase in reliability over vacuum tubes to be expected from solid state RF amplifying devices still in the laboratory stage? Furthermore, such optimizations are sensitive to the number and scheduling of missions to be undertaken. Uncertainties as exist at this stage of planning can significantly shift an optimal design.

At best one can create an integrated system that takes multiple advantage of the on-board equipment in an effort to maximize reliability, minimize development costs and minimize payload weights. In order to do this some common frequency must be chosen and some other compromises made. How does one weigh the advantages of a high gain antenna for altimetry against its disadvantages for following communication stations on the earth disc during cislunar flight?

This section does not attempt to strike such balances, but rather points out the compromises that have been made, the difficulties and possible solutions that potentially lie ahead as well as the advantages that accrue from the goal system.

A. Advantages

1. Minimal System Cost and Payload Weight

The system strives to minimize overall systems costs (including ground equipment) and payload fraction devoted to radiating electronic functions while maximizing, or meeting, an acceptable standard of reliability and versatility.

a. This goal is herein realized in a non-vacuous sense. We know of no way to make the payload devoted to these functions any less, except by (1) elimination of functions of (2) reduction in capability of specific functions. The actual payload weight is dependent on the specific capability (bits per second, altimeter range, etc.) demanded of each function.

b. A rational demonstration that total system cost is minimized is substantially more difficult. It is not practical, for example, to place a dollar value on payload weight since a reduction in weight may make some other functions more reliable or make weight available for that which might not otherwise fit on board. A more definitive statement on ground system cost must await our later study. However, the impact of this proposal on the ground system has been considered briefly.

c. Power consumption is minimized by making available a variety of combinations of equipments to meet both low and high capacity needs. By careful design the switching between modes can encourage low power consumption. Thus, the normal voice communications mode uses the on-board directional antenna and 1 watt driver. When an immediate need for voice or high capacity telemetry drops, the equipment can be arranged to switch back to the exciter (60 mw) with a respectable "keep-alive" telemetry capacity if the power-saving is desired. The total radiating systems energy consumption aboard the vehicle is directly proportional to the duty cycle of each equipment. To a first order approximation this is dependent only on operational considerations except for special equipments having large standby power drains. This type of standby is not apparently necessary in this proposal.

2. <u>Maximum Reliability</u>

By choosing to operate all of the equipment in a common frequency band we believe that the reliability and margins of the proposed system will exceed those of unintegrated systems of the same functional capability.

a. As indicated in Section II D, in the event of a single major component failure, operation in a time-shared or reduced capability mode is always possible. In many cases, multiple equipment failures are tolerable. The presence of the astronaut to do such switching makes the system practical.

b. Antennas can be shared or interchanged with a minimum of antenna drive, structural design and attitude problems.

c. By using only a single class of equipment, engineering attention can be focused on this class of equipment for reliability and efficiency rather than being dispersed across many equipments.

d. Within the Apollo lifetime one can expect a highly reliable and reasonably efficient solid state driverof respectable power to carry the backbone of the communications.

e. The vehicular equipment will gradually be qualified at a pace consistent with growth to lunar flight. Earth-orbital flights will be made with the lowest grade lunar communications link shown in Table I. The performance improvement possible (43.7 db) due to the difference between lunar ranges and earth orbital ranges permits a very acceptable performance at earth orbital ranges. A continuity of flight history of the lunar equipment from the start of the flight program will enhance reliability and minimize transitional operating problems.

f. All first order equipment failures are dealt with, by the astronauts, entirely by switching between major equipment components.

g. Caution has been exercised:

(1) to avoid excessive compromise of function

(2) to avoid time conflicts resulting from simultaneous demands for equipment

(3) to avoid a frequency choice having some specific disability that compromises all systems

(4) to insure equipment design that recognized the diversity of function (see Section IV C)

More will be said of these problems later in this section.

B. Caution Points

1. Frequency Choice

The preferred frequency band for the Apollo equipment will be 2.3 GC. The reasons for having this preference are:

a. The U.S. has taken a stand favoring the allocation of this band for space communications. The allocation is likely to be accepted by the International Telecommunications Union.

b. The frequency is close to optimum when noise considerations are appropriately weighed (see Appendix D). This is particularly true if the ground system can take advantage of the lower noise temperatures possible with the smaller ground antenna.

c. Advantage can be taken of the DSIF facilities for cis-lunar flight for special situations. Normal voice or telemetry is possible without an 85-foot antenna, so that this will enable the DSIF facilities to share time with other missions, yet to be called into action in an emergency or for higher quality circuits. In the later stages of the program, lunar flights may take place once per one or two months for a seven-day period. A 12.5 to 25 per cent loading of one third of the DSIF for Apollo might otherwise conflict with other deep space missions or special scientific occurrences.

This choice assumes that:

a. NASA will take a dominant position in the Interdepartmental Radio Advisory Commission (IRAC) on the allocation of frequencies and usage of this band. The bandwidth recommended to ITU is only 10 Mc wide.

b. NASA will control traffic and usage of this band to avoid conflicts within their house and with the Department of Defense.

c. It is assumed that an appropriate international frequency assignment will be made for the ground-to-vehicle frequency.

Sharing of the 2.3 GC band might appropriately be a cause for concern regarding mutual interference. Let us first consider the hazards of vehicular radiation at highest available power in a near-earth orbit passing directly over a DSIF station. The most difficult condition would occur when the vehicle is directly in the main beam ($\sim 0.33^{o}$) of the DSIF antenna. At 1400 n.m. this corresponds to an 8.4 n.m. circular window. The vehicle will pass through this window in 2 seconds. If the vehicle were to pass through the beam on each orbit and completely jam the DSIF, this would cause a loss of 4×10^{-4} of that data collected by the DSIF. In fact, however, an Apollo vehicle in a 300-nautical mile orbit at 35^{o} inclination will be in the main beam of one of the DSIF stations less than 10^{-4} per cent of the time (assuming the DSIF antennas are pointed at random but in such a way that it is possible for the vehicle to enter their beam). Thus, the probability of such an event is an order of magnitude less than the current design bit error probability accepted by the DSIF at design ranges of deep space and lunar probes.

A more likely occurrence is the introduction of unwanted energy into the sidelobes of the DSIF antenna. Again assume that the radiated signal from the vehicle is +13 dbw. The space loss at 300 miles is on the order of 154 db. Consider the significant side lobes of the DSIF antenna to be 0 db (while there will be larger side lobes than this, the probability of intersecting these is within one or two orders of magnitude of that indicated above). The signal reaching the receiver is, therefore, at -141 dbw. If all of the vehicular signals were in a pure carrier, a one cycle wide receiver offset from the carrier having a sensitivity of -220 dbw would require only 90 db of rejection. This is a quite reasonable design requirement at a suitable offset carrier frequency (and the transmitter would have to meet a -90 db spurious response specification) to essentially eliminate interference. Actually the receiver will have more bandwidth and be correspondingly less sensitive. Thus, frequency assignment for Apollo should differ from the DSIF by enough to guarantee 90 db of rejection by the DSIF receivers.

Thus it appears that except for spot passages through the DSIF beam, interference to the DSIF need be no problem. If this is still troublesome, arrangements might be made to momentarily shut down vehicular radiation during a near-earth DSIF transit.

In the reverse direction, the radiated DSIF signal will be more troublesome on the one hand because of the 10 kw ground transmitters and slightly less troublesome on the other hand due to the lower sensitivity of the vehicular receivers. This suggests that the vehicular receiver needs a 110 db spurious response specification to avoid difficulty due to side lobe radiation encountered in near-earth transits across DSIF facilities.

2. Illustrative Parameter Choices

A number of figures were chosen to illustrate a goal system design. While assumptions were indicated wherever they are used, it is worth collecting the assumptions in a single place.

a. It was assumed that a field-worthy amplifier will be available having a 1.5 db excess noise figure relative to 290° K. It was assumed that development would proceed toward the achievement of this amplifier. By comparison, the Mercury ground system achieved 3.5 to 6 db noise figures (conventional techniques) at about 250 mc.

b. The vehicular antennas present special problems discussed more fully in Section IV. In particular, the "isotropic" Mercury vehicular antenna (C-band) was -20 db to -30 db below the 0 db antenna specified. This must be improved to 0 db or the corresponding penalty paid in power.

c. The bandwidths shown in Table I are wholly available for signalling only if techniques at least as efficient as single side band transmission and reception or double side band with coherent detection or similar system is used.

d. Cable and other loss allowances are not extravagant. They do not leave room for equipments to be dispersed in stray corners all through the module. In addition to electrical penalties, there is a penalty for added cable weight for extra length runs (with attendant opportunities for noise pickup and interference). Two of the study contractors devoted a substantial fraction of electronic systems weight to structure and harnessing (up to 50 per cent).

C. Equipment Design Problems and Compromises

As has been indicated, one of the prices of multiple-use systems design is a tightly integrated design and some compromises in performance of subsystems. This section will detail some of these compromises.

1. Frequency Switching

In order to use the same transmitter and receiver for an active ranging role and a communication system, they must be capable of having their frequency of operation switched. Considering the possibility of allowing either driver and either receiver to serve both functions, at least the following design possibilities exist.

a. Keep the main transmitter chain on one frequency (f_1) and the alternate on another frequency (f_2). This requires that both receivers be capable of switching among four frequencies f_1, f_2 (for altimetry or rendezvous ranging) and the appropriate offset communication frequencies for f_1 and f_2 (i. e., $f_1 - f_1$, $f_2 - f_2$).

b. Require both transmitter chains to be capable of transmitting of f_1 or f_2. This will require each receiver to be capable of receiving on only two frequencies, either f_1 and ($f_2 - f_2$) or f_2 and ($f_2 - f_2$), where $f_2 - F_2$ is the ground transmitter frequency.

The choice among these alternatives depends on the relative difficulty of building two-frequency transmitter chains, of building four-frequency receivers (see next section) and of making the ground transmitting and receiving systems agile in frequency. (The larger ground transmitters present a special problem in this regard.)

At this point, all of the advantages of the goal system can be lost. For example, if a two-frequency transmitter is equivalent in complexity to two transmitters (except for the use of a single active output element), nothing has been gained. Poor design can readily achieve this!

2. Switchable Low Noise Receivers

One element that does not lend itself to ready switching is the low noise front end of a receiver. At this stage of technology this unit is carefully optimized for a single frequency in order to achieve low noise. One solution would be to engineer the diplexers and duplexers with wide band low noise front ends as part of their design. The switching is then accomplished by connection of the mixer and appropriate local oscillator stages to the diplexer or duplexer outputs. This is one example of system design integration. The spurious output of the transmitters must be held below detectability.

3. Switching

The capability for achieving reliability through multiple use of equipment blocks comes at the cost of being able to switch between blocks. This capability has a non-vanishing cost (one of the study contractors recognized this and alloted 7.5 per cent of electronic weight to coaxial switches). The most obvious way to do switching is through coaxial switches located in the equipment. Coaxial switches have been the cause of some concern regarding reliability under adverse vibration.

Alternatives exist. One possibility at the UHF stages are appropriately phased bridge structures, perhaps even using magnetically biased ferrite elements. Another is to bring the equipment near an accessible point to the astronaut (to conserve on long cable runs) and to use cable patching. This has an added advantage of making key points accessible for pre-launch checkout and in-flight failure sensing.

4. Choice of Design Parameters

The normal design of receivers requires a choice of intermediate frequencies and bandwidths. If full advantage is to be taken of the goal system, these choices must be carefully made so that a single receiver i.f. strip could be used for range code acquisition and for the most precise rendezvous and altimetry ranging (e.g., for 1 μs pulses). The second i.f. bandwidth might well be chosen for less precise altimetry and for longer pulses needed for augmented rendezvous ranges.

5. Frequency Optimization

The optimal frequency choice for a cis-lunar communication system and a lunar altimeter are not coincident. Appendix D has already been cited to indicate that, in the basis of lunar temperatures, the optimum frequency is a function of dish size, with the smaller antennas favoring the region of 2-3 GC, but not strongly. The broader beamwidth at the lower frequencies (for constant antenna area) also makes the task of antenna pointing easier.

For ranging on non-transponding targets (moon, earth, dead satellites) there is a payload weight advantage to going to higher frequencies by the square of the wavelength ratio. This is partially or wholly offset by the decrease in efficiency of output power stages and/or the inability to make coherent detections. Further, the higher frequencies demand greater structural tolerance of the antenna in order to achieve the higher gains possible in the same dish size.

6. Modulation

All of the well-designed communication modulation systems that are directed toward minimizing transmitter power use some form of modulated continuous wave (e.g., FM or PM). These give a continuous carrier phase reference for tracking and generally demand an average-power-limited-transmitter.

On the other hand, this comes into conflict with the ranging systems. While there are a number of ranging systems that employ modulated continuous radiation (like the proposed JPL system), these are generally employed in single transponder situations. Where used in altimetry and radar ranging, these do not discriminate well against multiple or dispersed targets. Thus, a time-extended target (such as the moon as seen from cis-lunar space) is best ranged against by pulsed techniques for highest accuracy because the detection and display techniques are simpler, and human discrimination of targets is better.

Summary:

The illustrative parameters used in describing one possible set of parameters for the goal system are not unique. Other equivalent designs can be formulated and should be considered. While there is some compromise of function in going to a single system, the compromises are acceptable.

V. Other System Considerations

A. Antennas

Two types of antennas are required for the vehicle: isotropic and directional. It is difficult to make anything but general statements without interacting with the structure design and equipment layout. Some bounds on this discussion are offered below.

1. Isotropic

The "isotropic" antenna will find its principal application in the near-earth orbit, but this "isotropic" antenna should be useful as a communication backup during lunar flight at reduced capacity. The pattern on the "isotropic" antenna should be such that the received signal strength rarely, if ever, falls below a known level for all capsule attitudes and positions with respect to earth bound stations. From practical considerations, the achievement of true isotropic radiation appears to be difficult on a body, with a small number of radiators, having the dimensions of the Apollo vehicle. From a practical example, the Ranger, being constructed by the Jet Propulsion Laboratory, is being designed to have no nulls deeper than 5 db below isotropic. The Apollo vehicle is substantially larger than Ranger. It appears at this time to be impractical to have a single radiator or small number of simultaneously excited radiators attached to the vehicle that will approximate this performance.

At the expense of requiring the astronaut to select among two or three radiators, it appears possible to have one-half spherical or one-third spherical coverage with no regions falling below isotropic coverage. It may even be necessary to consider mounting these antennas on outriggers normally on the vehicle (e.g., solar panels). If such booms are indeed important but unacceptable for aesthetic or other reasons, the alternatives may be larger number of such antennas, more receivers, an increase of required transmitter power or other weighty solutions. It should be recalled that this problem arose with the C-band slot antennas on Mercury and required phase shifting at an audio rate. The power penalty and restrictions on modulation must be carefully considered if this alternative is forced.

It is virtually essential that the "omni" or "isotropic" coverage be arranged, in near-earth orbits, so as to avoid antenna switching for the normal capsule attitude in a single transit of one site. (This suggests the proposed limit of two or at most three antennas.) This limitation is set because antenna switching time is difficult to predict and manually execute during the short time of passage across one site.

During lunar flight a modest amount of switching should be acceptable (e.g., no more than once per hour).

Other alternatives can be considered to that of manual switching. One alternative is automatic sampling of the output of each of the elements of the "isotropic" radiator and selection of one of these. The switch would stay on this element until the signal fell below an acceptable level and then the search would start anew. This alternative would have to be employed for both the transmitter and receiver. It would probably require the re-acquisition of carrier and ranging codes after each antenna switch.

The second alternative would be to employ multiple receivers in an optimal diversity combining mode. The multiplicity of receivers adds to the payload weight. It is illustrative of the severe penalties that may be needed to achieve adequate antenna performance.

If complete loss of vehicular attitude control occurs with tumbling, the simultaneous degradation of communications would have to be accepted under some of the above modes. This may also be a complication to be considered in all artificial gravity proposals involving vehicular rotation.

2. Directional Antennas

The directional antenna aboard the vehicle will be useful for all communications in cis-lunar space and for the electromagnetic guidance systems in near-earth as well as lunar situations.

The weight of the directional antenna, booms, drive motors, servos and associated cables increases the antenna size, complexity, and reliability and must be balanced against the decrease in average power required of vehicular transmitter and power supplies. It now seems likely that other considerations than weight balance will set an upper bound on antenna size.

For communication purposes a reasonable upper bound on antenna size might be established by that point in cis-lunar space where the directional antenna can be pointed at the earth so that the earth disc either fills the entire antenna beam or no continuous corrections by precise pointing data is needed for a particular site on earth. As has been pointed out earlier, the addition of tracking circuits using the received signal for error deviation complicates both the antenna and receiver. If the earth disc wholly fills the antenna, then other sensors (like photo sensors) can be employed, but for tracking specific stations on earth, these are of no assistance.

The first condition makes for acceptable vehicular antenna gains (e. g., at 20,000 miles from the center of the earth, the allowable angle is 11.5°, the consequent gain at 2.3 GC is 23 db. At this point also the space loss will have increased by 20 db over the worst loss on near-earth orbit, just compensated for by the antenna). At ranges like 20,000 miles the angular rotation of the line of sight from the vehicle to a point on earth is sufficiently slow so that coverage of half of the angular earth disc permits acceptably infrequent angular corrections of limited precision. This suggests an upper bound of something like 4 feet (1.23 meters) on dish diameter in the absence of precision pointing and tracking circuits.

A minimal acceptable antenna gain is 15-18 db over the "isotropic" antenna (corresponding to a dish diameter of 1.25 feet). Lesser gains do not make significant enough improvements to warrant employment.

For guidance purposes, particularly altimetry and rendezvous ranging against quiet targets, one would like to have larger antennas because the received signal goes as D^4 (rather than as D^2 in the communications case). If angle measurements are ever desired, with suitably precise mounting, measurements made with the larger dishes are more accurate. Considering these conflicting requirements, dish diameters of 4 feet appear to be a reasonable compromise, with antennas of less than 1.25 feet unacceptable and antennas in excess of 4 feet in size still open to consideration. Note also that beam symmetry is not as important as in normal radar design, thus opening the way for oddly shaped antennas fitting into non-circular parts of the structure.

There should be at least two directional antennas (not necessarily of identical size) for redundancy and for simultaneous usage in communication to earth while performing lunar altimetry or rendezvous ranging. These need not be symmetrically placed but each should, by vehicle attitude changes, be capable of performing the task of the other.

Consideration was given to problems of antenna pointing. The addition of automatic tracking and angle measurements presents a substantial increase in vehicular complexity that does not seem warranted in the early stages of vehicle development. This will become useful, if not necessary, for long range target pickup under rendezvous conditions. (See Appendix C.) Prior to that time some signal strength and angle repeaters will be adequate for pointing the earth or moon. Development should be initiated on reasonable methods of angle measurements, perhaps by taking advantage of two on-board directional antennas.

B. Electrical Interfaces

The interfaces between the vehicular electronic system described in this report and other subsystems of the Apollo vehicle are with the ground transmissions of the ground-vehicle RF link, with the ground reception of vehicular transmissions, into the on-board computer, out of the on-board computer, into and out of the voice system, out of the TV system, and out of the telemetry sensors. In addition to these, the vehicular timing system has also been mentioned as having an interface with these systems. It is the purpose of this section to explore these interfaces, to define them better, and to recommend the kind of standards or specifications to be used at each.

At each of these interfaces, the specification should be at a minimum rather than a maximum. Hopefully the Apollo vehicle or its components will evolve into future manned flight capsules. Room must be allowed for growth in requirements and performance as well as the technical state of the art to meet these requirements. Interface specifications should not limit this growth, neither should they be excessively constraining so that independent subsystem design is impossible.

1. Ground Transmissions

Specifications are required on:

a. Frequency

b. Frequency stability, short and long term

c. Modulation, where the modulation is used aboard the vehicle, or bandwidth and amplitude and phase distortion (or impulse response) in this bandwidth, where the modulation is re-transmitted without narrow-banding.

d. Signal level, including nominal polarization losses. Where the position-finding modulation is not used (e. g., demodulated) aboard the vehicle, one should avoid being rigid about its specification except for bandwidth and fidelity of re-transmission. This would allow the type of modulating signal to be varied with the phase of the mission, the sophistication of position-finding code theory, etc. The bandwidth is established by the desired accuracy of range measurement.

The same remarks are not applicable to command or voice transmissions that must be demodulated and used aboard the vehicle. These are discussed later.

2. Vehicle Transmissions

a. Frequency

b. Frequency stability, short and long term

c. Modulation (see prior remarks)

d. Minimal radiated signal level

3. Digital Data for the On-Board Computer

The output of the communications receiver must be specified. The specifications should include the form of the serial data signals (mark and space), the shape and timing of timing and word synchronization signals. All of these output signals should be narrow band (no impulses or rectangular pulses to avoid generating interference or being susceptible to interference) dipulses. Word length in bits and bit significance ordering must await the design of computer and buffering (see Section 6 below). In deciding these, provision should be made for the future addition of parity check bits or words of substantially more complexity than simple odd-even checks.

4. Digital Data from the On-Board Computer

The output of the computer will probably come to the digital data transmitter through a buffer. Here it may be mixed with other telemetry sensors and voice sources. The specification on the output of the buffer should be identical to the specification on the output of the communication receiver. It would be wise, in the buffer design, to permit the possibility of accepting buffer read-out timing from a source in the transmitter if later developments should demonstrate gains from associating the timing with the transmitted carrier frequency.

5. Voice

The output of the voice receiver should be typical audio bandwidths at some level suitable to the voice distribution system. The exact bandwidth and level specifications need not be rigidly prescribed now.

The transmitter will probably require a direct voice modulation input from the audio system as well as a digitalized voice signal processed and mixed with the telemetry signals in the buffer. Any voice processing (e. g., peak clipping) should be done by the transmitter.

6. Telemetry and TV

It is assumed here that the transmitter will have provision for serial digital transmission of bit data, sync and timing. A buffer must exist between the telemetry and TV sensors to connect these to digital form, and mix with voice if necessary, for delivery to the transmitter.

With a long lived program such as Apollo, avoidance of concepts that lead to lack of flexibility or growth potential appears mandatory. In this sense a pulse code modulation system has been recommended (as will be discussed in a later appendix) for the primary means of vehicular-ground communications. One of the prime features of this system is the inherent flexibility and growth capability that can be achieved through the use of digital techniques.

It is similarly necessary that the on-board equipment interacting with this communications system also be designed so as not to constrain their future evolution. At present the vehicle-to-ground communications have been thought of as transmitting various telemetry data and indicating vehicle status, on-board computer outputs, voice, TV, and possibly other external vehicle sensors, such as radiation, etc. The ground-vehicle communications link will carry voice, reference data for the computer for on-board inertial platform, command data, and possibly display information.

For these things to be properly integrated, some digital buffering must be provided for the purpose of directing data to the proper display or computer. Similarly the information to the ground must be properly coded to indicate the data being supplied. In addition, any error detection or correction coding could be introduced or verified through the use of this digital control equipment. Similarly, if bit rates are to be varied depending upon the communication distance to be covered, allowances will have to be made by this equipment in sampling the various sensors.

It is well within the state of the art to consider that such a buffer could be designed to use little power, be small in size and weight, yet keeping the required amount of flexibility. This flexibility can presumably be achieved through the use of essentially modular elements. It is not inconceivable to think of designing the buffer and constructing it some months ahead in a fashion that meets the requirements for each of the planned missions. While this does not allow the maximum flexibility for a particular mission, it will allow, with some moderate lead time, the use of the same type of equipment for various objectives in different missions while at the same time utilizing minimum of weight and space.

7. Timing

We do not now recommend that the central timing be used to directly control communication carrier frequencies or data timing. While this has attraction on paper, such a proposal creates too tight a design constraint having no commensurate significant advantages.

C. Functional and Physical Interfaces

There are a number of other parts of the Apollo vehicle whose functional, physical, and operational design interacts with the communications and position-finding system. These points of interaction are briefly listed here as reminders.

1. RF Interference

All equipment in the vehicle that uses or generates electrical power is a potential source of interference or is potentially susceptible to interference from other such equipment. Each supplier of such equipment should be aware that this equipment cannot be considered as qualified until it is tested in place on the capsule, connected to the capsule power system and tested with suitably sensitive capsule receiving and audio equipment

2. Antenna and Structural Design

Aside from the obvious physical problems of mounting, erecting and orienting directional antennas, the capsule structural designers must also recognize the difficulties and needs for securing substantially omni-directional radiation from the capsule. This may require the placement of a large number of slots in the surface or the use of antennas on booms.

3. Guidance

Since control is presently planned to be on-board and it is expected that on-board optical devices will be adequate to carry out Apollo missions safely, it is reasonable to assume that ground information will be used only as a backup unless it can significantly improve the performance of the vehicle or the probability of a successful mission.

During most of the Apollo flights, however, the ground tracking network will be able to provide navigational information better by at least an order of magnitude than that obtained from the on-board equipment, particularly if provisions are made to telemeter accelerometer data to the ground after periods of thrusting. If there are any advantages to having more precise navigational information, these ground data should be exploited by the guidance system either as primary data or as a check of on-board equipment.

Studies are not yet available that give the detailed trade-offs in vehicular guidance information accuracy and energy savings.

4. Vehicle Power

Aside from obvious questions of voltage level, transient regulation in face of large loads from high energy equipment and long-term regulation, the vehicular power system is of concern as a source and carrier of interfering signals. In addition to conducting paths into sensitive receivers and audio systems, interference on the vehicular power cables can be inductively or capacitatively coupled into long parallel runs of wire. Filtering should be provided at a number of points in the electrical power system and consideration given to separately enclosed cable runs for signalling and audio wiring.

5. Antennas and Vehicle Operations

The requirement for pointing directional antennas for altimetry or rendezvous ranging or for choosing among isotropic antennas creates an interaction with the attitude of the vehicle for propulsion, sun shielding of the cryogenic fuel, etc. The final placement of antennas should, therefore, be checked to be sure that no conflicts have been built in. This problem could become acute with rotation for artificial gravity.

6. Accessibility, Maintenance and Launch Checkout

It seems redundant to suggest that all of the capsule electronic systems shall be capable of removal and replacement, from the normal capsule checkout position, in relatively short time (minutes). Launch checkout should permit a quantitative checkout of in-place receiver sensitivity, transmitter power output and end-to-end checks of systems function. The electronic packages should have failure sensors or other maintenance checks to permit on-board isolation of failed blocks from the operating position and substitution by switch action.

7. Trajectory and Ground Monitoring

There are two critical portions of a lunar trajectory where ground monitoring could be of substantial assistance, either as a means of monitoring (i.e., observing) or "backing-up" (capable of augmenting or replacing, in the event of failure) on-board performance. In order that either of these functions be performed there is some constraint on trajectories or some substantial expense in ground equipments. Without attempting to anticipate all of the results of our later study of the ground network, there are some obvious conclusions that can now be stated about lunar injection and re-entry.

a. Lunar Injection

There are two portions of lunar injection to be considered. The first is concerned with monitoring velocity cutoff, while the second is concerned with monitoring of the transfer ellipse to accumulate as much statistical data as early as possible to permit an early and, consequently energy saving, mid-course correction. Both affect the ground network in the same way; electromagnetic line-of-sight must be available between the vehicle and the ground station. Prior to thrusting from a 100 n. m. parking orbit, the ground-projected line-of-sight from a ground station is about 800 n. m. Thus, if it is desired to launch at any time during the lunar cycle, an excessive number of injection monitoring sites will be required or serious constraints on the choice of trajectories must be accepted. There may be problems of flame attenuation. For monitoring post-burnout flight, matters are eased somewhat by the increased altitude of the vehicle.

In either case, the placement of the injection monitoring station or stations is closely related to the choice of trajectory. The emplacement of such station, with a precision commensurate with its backup function, does not appear to be the task of a truly mobile station. Further, if the sub-injection point is in unfriendly territory or in the ocean areas, the problems are further complicated.

b. Re-entry

During re-entry, the vehicle can undergo voluntary changes, of course, without being able to communicate these to the ground network. As a monitor of vehicle motion and as a means of insuring rapid recovery post-impact, it would be wise to track the vehicle through as much of the re-entry trajectory as would assure no loss of track. This task becomes substantially more difficult and expensive if the re-entry occurs over ocean areas without suitably spaced island bases. This is another constraint on the re-entry trajectory.

APPENDIX A

Alternative Grades of Communication Service and Their Choice

by

H. Sherman

Independently of the number of equipments required for reliability, certain types of equipment are minimal, including:

Isotropic Antenna
Directional Antenna
Final Amplifier
Driver Amplifier
Exciter Amplifier
Receiver
Ground Station (differ primarily in antenna size)

These can be organized into 2 x 3 x 2 = 12 different combinations for vehicle-to-ground transmission. It is possible that some combinations could be below ground system detectability. How should the remainder be organized?

For earth transmission grades the 43.5 db difference due to proximity of the vehicle in near-earth orbits $(210,000 \text{ n.m.}/1400\text{n.m.})^2$ makes the 0 db lunar system a superior grade of near-earth service. On the other hand, the variety of near-earth service achievable is substantially less because the directional antennas on the vehicle are not recommended for the automatic tracking required in near-earth orbits nor can one assure that the DSIF 85-foot antenna will be capable of following near-earth vehicles without exceeding design angular following rates. As will be shown on later circuit quality analyses, the near-earth service is good. The major discussion of grades of transmission service, therefore, centers on lunar flight.

Simplicity suggests that the number of different communication combinations should be limited to permit standardization of receiver bandwidths and communication bit rates. This is most effectively accomplished by grouping all modes between the lowest and highest into a small number of classes (i.e., either two or three grades).

Let:

G_{VA} = gain of vehicular directional antenna over the vehicular isotropic

G_F = gain of vehicular final amplifier over the intermediate power stage

G_{GA} = gain of 85-foot antenna over "small" ground antenna.

The composite gains of each of these classes are G_{VA}, G_F, G_{GA}, $G_{VA} + G_{GA}$, $G_{VA} + G_F$, $G_F + G_{GA}$, if we ignore the exciter.*

If we choose to insist on grouping these into two classes (other than the lowest and highest grades of service), then

$$G_{VA} = G_F = G_{GA}.$$

There is only one way in which a grouping into three classes can occur. If two of the gains are equal and their sum is that of the third gain, then the grades have gains O, G, 2G, 3G, 4G where G is the gain of the two with equal gain. All other arrangements lead either to 7 or 8 grades of service (ignoring the exciter).

The proposed number of grades of service and their organization is shown in Table A-1. The recommendation arises from considering the different communication services needed. What types of service can be identified?

1. Acquisition signal adequate to insure that a 39 db ground station can acquire a minimum radiation from the capsule (e.g., with directional antenna and final amplifier out-of-service) in a reasonable search time. The sole capability would be the location of the vehicle in space.

2. "Keep-alive". Enough carrier will be provided to insure carrier phase lock; signal power will be of adequate bandwidth to reassure the ground that the capsule and personnel are functioning, but have no communication traffic to pass. In this mode a minimal demand may be made on the ground facilities.

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* The use of the exciter is primarily for reliability. It is assumed that the final stage has enough gain to deliver a respectable output from the exciter alone, if necessary. One of the reasons for disregarding the energy savings of going to the exciter is that some lower limit exists on a useful saving of power aboard the vehicle either because the saving is in the "noise" (i.e., it is the order of the uncertainty in power consumption of other devices) or because at the lower power levels the efficiency falls off due to the presence of overhead tasks (relays, filaments, magnetic biases, etc.).

TABLE. I
COMMUNICATION COMBINATIONS

1. The basis for the bandwidth calculations shown are given in this Appendix and include the following assumptions: carrier phase-lock operation in a 20 cps bandwidth having a 6 db carrier-to-noise power ratio, 1.5 db noise figure preamplifiers (relative to 290° K), 7 db margin, modest allowances for cable and other losses in vehicle and ground, 10 db signal-to-noise ratio in the signalling bandwidth, orthogonal polarization sensing and polarization combining on the ground, 0 db "half-omni" antenna, 26.5 db vehicular directional antenna, 2.3 GC.

2. The db rating of Transmission Grade is not directly interpretable as bandwidth ratio change.

3. The cross-hatched areas, <u>26 db, Mode A</u> and the <u>Near-Earth Transmission Grade</u>, are proposed to be the normal earth and lunar operating modes.

4. Modes A, B or C identify alternate combinations of equipments having approximately the same grade of performance.

B-13650-7

LUNAR TRANSMISSION GRADE	0 db	13 db			26 db			39 db		52 db
+10db S/N BANDWIDTH	----	120 cps			3 kc			63 kc		1.25 Mc
MODE		A	B	C	A	B	C	A	B	
VEHICULAR ANTENNA										
ISOTROPIC	x	x	x				x			
DIRECTIONAL (26 db)				x	x	x		x	x	x
VEHICULAR POWER										
EXCITER (60 mw)				x		x				
DRIVER (1 watt)	x		x		x			x		
FINAL (20 watt)		x					x		x	x
GROUND ANTENNA										
39 db	x	x		x	x				x	
53 db			x			x	x	x		x
NEAR-EARTH TRANS. GRADE	+44 db	+57 db								
+ 10 db S/N BANDWIDTH	125 kc	2.5 Mc								

COMMUNICATION COMBINATIONS

TABLE A-1

3. Emergency mode. Enough carrier power must be provided for carrier phase lock. Enough bandwidth will be provided for emergency communications with a maximal demand on ground facilities.
4. Telemetry
5. Voice
6. Range Transponding
7. TV
8. Combinations of the last four.

It is not necessary that all of these grades of service be different, although normally they will be, with increasing bandwidth requirements in the order shown.

Acquisition service is basic to all others in the sense that carrier phase-lock is assumed in all other grades of service. Search time to achieve phase-lock can be minimized by augmenting carrier power and opening the search bandwidth. Once carrier phase-lock is achieved, phase-lock bandwidth can be reduced and a commensurate fraction of power can be diverted from the carrier to signalling.

The absolute level of the remaining grades of service are somewhat arbitrary. <u>Examples</u> (rather than requirements) are given in Table A-II.

TABLE A-II

Examples of Bit Rates and Bandwidths

	Bandwidth	Bit Rate
"Keep-alive"	20 cps (1)	
Emergency		40 bits/sec (2)
Telemetry	240 cps (3)	1.5×10^3 bits/sec
		10^4 to 5×10^4 bits/sec (4)
Voice	3 kc	10^4 to 3×10^4 bits/sec (5)
"TV"	3 kc - 6 MC	

Notes:

1. This might be a single channel quantized EKG of the Duty Astronaut.
2. This would correspond to high grade code or teletype service.
3. Mercury telemetry has a total effective bandwidth of about 240 cycles excluding inter-channel guard bands. The actual bit equivalent assumes 2 per cent precision with 10 per cent allowance for synch information.
4. Figures between 10^4 and 5×10^4 bits per second have been frequently referenced by the study contractors.
5. 10^4 to 3×10^4 bits per second are presently required for moderately acceptable digitalized voice using straight PCM.
6. If facsimile is included as the lower end of a visual transmission system and color TV is the upper bound, the range is shown above.

The useful grades of service are recommended for grouping into the following classes:

1. Keep-alive and emergency. The emphasis for this class of service is minimum power consumption and simplicity of demands on the equipment.
2. Voice or Telemetry. This should be the normal mode of operation. It would be nice but not essential that both voice and telemetry could be sustained at once. As the "utility" mode, the organization of equipment should be direct and simple, probably with a fixed telemetry format of basic information.
3. Mixed Voice and Telemetry. This service would give simultaneous voice and telemetry of high quality and considerable flexibility for capsule qualification or for experimental transmissions.
4. TV or High Quality Service. This would be an upper bound on vehicular performance, demanding the most of capsule and ground equipment.

Table A-III shows the proposed groupings recommended.

The absolute level or bandwidth for each grade of service cannot be derived formally. Nor is there any "scientific" way for specifying the safety margin to be built into each circuit. There is a strong impulse to design conservatively as a guarantee that the system will work, yet this creates a weight penalty. In the following a stand has been taken that is not conservative in the sense that no allowance is made for tolerances (i. e., it is assumed that each component performs exactly as shown under the worse combination of conditions and that all variables of the communication path are known and under control). Should more conservative design be desirable, or more safety margin allowed, then power outputs or antenna gains should be increased.

The following tables give the basis for calculating circuit quality.*
These assume that the transmission path is above the horizon by at least a half beamwidth of the antenna so that ground reflections are of no concern.

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* Note that the excess noise figure and threshold requirements for signal have been given negative signs to indicate these are effectively signal losses over an ideal that must be charged to the signal path.

The receiver is described by the ideal noise power per one cycle of bandwidth at 290°K. Any excess of available signal can be distributed either to margin (or safety factor) or to opening the receiver bandwidth (and, therefore, admitting more noise).

TABLE A-III

COMMUNICATION FUNCTIONS

Mode	Lunar Trans. Grade	BW (cps.)	LUNAR Function	BW	EARTH Function	Mode
	0 db	0	UNUSED	125 Kc	COMBINED VOICE AND TELEMETRY NORMALLY USED.	
A			KEEP-ALIVE (OR EMERG:	2.5 Mc	TV	A
B	+13 db	120			not used because of angular following rate demanded of directional antennas	B
C			(normal non-traffic mode)			C
A			(normal traffic mode)			
B	+26 db	3 Kc	VOICE OR TELEMETRY			
C						
A	+39 db	63 Kc	MIXED DIGITALIZED VOICE AND TELEMETRY			
B						
	+52 db	1.25 Mc	MIXED DIGITALIZED VOICE, TELEMETRY AND T. V.			

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	0 dbw			
Carrier	0 dbw			
Signal				
Mismatch Loss	-0.5 db			
Diplexer Loss	0	(4)		
Cable Loss	-0.5 db			
Ant. Pointing Loss	0			
Veh. Ant. Gain	0 db	(3)		
Space Loss	-212 db			
Ant. Pointing Loss	-0.5 db			
Ground Ant. Gain	+39 db			
Polarization Loss	-1.0 db	(1)		
Cable Loss	-1.0 db			
Diplexer	-0.5 db			
Excess Noise Figure over ideal	-1.5 db	(2)		
Threshold S/N	-6.0 db			
Available Signal	-184 dbw			
Ideal 290° Recvr N_o	-204 dbw			
Excess Signal	+20 db			
Margin	+ 7 db			
Bandwidth	20 cps			

Service:	0 db Trans.
Vehicular Ant:	Isotropic
Vehicular Power:	1 watt final
Ground Antenna:	39 db

Notes:

1. The ground equipment will include orthogonal polarization ant. feeds with some form of near optimum combining. No polarization tracking assumed. 2. All noise fig. are referenced to 290°K (assuming the antenna noise is dominated by a full 290°K lunar disc). No credit is given here for the apparent reduction in ant. temp. due to partial occupancy of the ant. beam by the lunar disc. 3. The vehicular ant. is a half-omni (e.g., cardioid) having a min. gain of 0 db over isotropic in the useful solid angle of the ant. 4. In all cases it is assumed that there is no diplexer because the transmitter is connected to one antenna, while the receiver is connected to another.

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	0 dbw			
Carrier	-13 dbw			
Signal			-0.2 dbw	
Mismatch Loss	-0.5		-0.5	
Diplexer Loss	0		0	
Cable Loss	-0.5		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	0		0	
Space Loss	-212		-212	
Ant. Pointing Loss	-1.0		-1.0	
Ground Ant. Gain	+53		+53	
Polarization Loss	-1,0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5 db		-1.5	
Threshold S/N	-6.0	(1)	-10	(2)
Available Signal	-184 dbw		-175.2	
Ideal 290° Recvr N_o	-204 dbw		-204	
Excess Signal	+20 db		+29 db	
Margin	+ 7 db		+7db	
Bandwidth	20 cps		160 cps	

Notes:

Service:	13 db Trans.
Vehicular Ant:	Isotropic
Vehicular Power:	1 watt final
Ground Antenna:	53 db

1. For initial acquisition, all of the available transmitted power can be devoted to the carrier. This power increase permits the expansion of phase-lock bandwidth to reduce acquisition search time. 2. This permits a probability of error of 10^{-5} for differentially coherent PSK.

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	13 dbw			
Carrier	+0.5 dbw			
Signal			+12.5dbw	
Mismatch Loss	-0.5		-0.5	
Diplexer Loss	0		0	
Cable Loss	-0.5		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	0		0	
Space Loss	-212		-212	
Ant. Pointing Loss	-0.5		-0.5	
Ground Ant. Gain	+39		+39	
Polarization Loss	-1.0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5		-1.5	
Threshold S/N	-6.0		-10	
Available Signal	-184 db		-176 dbw	
Ideal 290° Recvr N_o	-204 dbw		-204 dbw	
Excess Signal	+20 db		+28 db	
Margin	+7 db		+7db	
Bandwidth	20 cps		120 cps	

Notes:

Service:	13 db Trans
Vehicular Ant:	Omni
Vehicular Power:	20 watts final
Ground Antenna:	39 db

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	- 12 dbw			
Carrier	-25.5 dbw			
Signal			-13.5 dbw	
Mismatch Loss	-0.5		-0.5	
Diplexer Loss	0		0	
Cable Loss	-0.5		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	+26 db		+26	
Space Loss	-212		-212	
Ant. Pointing Loss	-0.5		-0.5	
Ground Ant. Gain	+39		+39	
Polarization Loss	-1.0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5		-1.5	
Threshold S/N	-6.0		-10.0	
Available Signal	-184 db		-176.5 dbw	
Ideal 290° Recvr N_o	-204 dbw		-204 dbw	
Excess Signal	+20 db		+27.5 db	
Margin	+7 db		+7 db	
Bandwidth	20 cps		120 cps	

Notes:

Service: 13 db Transmission

Vehicular Ant: 26 db

Vehicular Power: 60 mw exciter

Ground Antenna: 39 db

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	-12 dbw			
Carrier	-39 dbw			
Signal			-12 dbw	
Mismatch Loss	-0.5 db		-0.5	
Diplexer Loss	0		0	
Cable Loss	-0.5 db		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	+26 db		+26 db	
Space Loss	-212 db		-212	
Ant. Pointing Loss	-1.0		-1.0	
Ground Ant. Gain	+53 db		+53 db	
Polarization Loss	-1.0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5		-1.5	
Threshold S/N	-6.0		-10	
Available Signal	-184 dbw		-161 dbw	
Ideal 290° Recvr N_o	-204		-204	
Excess Signal	+20 db		+43 db	
Margin	+7 db		+7 db	
Bandwidth	20 cps		4 kc	

Notes:

Service:	26 db trans
Vehicular Ant:	Directional
Vehicular Power:	60 mw exciter
Ground Antenna:	53 db

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	0dbw			
Carrier	-25.5dbw			
Signal			0 dbw	
Mismatch Loss	-0.5		-0.5	
Diplexer Loss	0		0	
Cable Loss	-0.5		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	+26 db		+26 db	
Space Loss	-212		-212	
Ant. Pointing Loss	-0.5		-0.5	
Ground Ant. Gain	+39		+39	
Polarization Loss	-1.0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5		-1.5	
Threshold S/N	-6 db		-10	
Available Signal	-184		-162.5	
Ideal 290° Recvr N_o	-204 dbw		-204 dbw	
Excess Signal	+ 20 db		+41.5 db	
Margin	+ 7 db		+7 db	
Bandwidth	20 cps		2.82 kc	

Notes:

Service:	26 db trans
Vehicular Ant:	Directional
Vehicular Power:	1 watt final
Ground Antenna:	39 db

CIRCUIT QUALITY CHART

	Carrier		Signal	
		Notes		Notes
Transmitter Power	+13 dbw			
Carrier	-13 dbw			
Signal			+13 dbw	
Mismatch Loss	-0.5		-0.5	
Diplexer Loss	0		-0	
Cable Loss	-0.5		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	0		0	
Space Loss	-212		-212	
Ant. Pointing Loss	-1.0		-1.0	
Ground Ant. Gain	+53		+53	
Polarization Loss	-1.0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5		-1.5	
Threshold S/N	-6.0		-10	
Available Signal	-184 dbw		-162 dbw	
Ideal 290° Recvr N_o	-204		-204	
Excess Signal	+20 db		+42 db	
Margin	+7 db		+7 db	
Bandwidth	20 cps		3.1 Kc	

Notes:

Service: 26 db Transmission

Vehicular Ant: Omni

Vehicular Power: 20 Watt Final

Ground Antenna: 39 db

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	0 dbw			
Carrier				
Signal			0 dbw	
Mismatch Loss			-0.5	
Diplexer Loss			0	
Cable Loss			-0.5	
Ant. Pointing Loss			0	
Veh. Ant. Gain			+26 db	
Space Loss			-212	
Ant. Pointing Loss			-1.0	
Ground Ant. Gain			+53	
Polarization Loss			-1.0	
Cable Loss			-1.0	
Diplexer			-0.5	
Excess Noise Figure over ideal			-1.5	
Threshold S/N			-10	
Available Signal			-149 dbw	
Ideal 290° Recvr N_o			-204 dbw	
Excess Signal			+55 db	
Margin			+7 db	
Bandwidth			63 Kc	

Notes:

Service: 39 db Transmission

Vehicular Ant: Directional

Vehicular Power: 1 Watt Final

Ground Antenna: 53 db

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power				
Carrier				
Signal			+13 dbw	
Mismatch Loss			-0.5	
Diplexer Loss			0	
Cable Loss			-0.5	
Ant. Pointing Loss			0	
Veh. Ant. Gain			+26 db	
Space Loss			-212	
Ant. Pointing Loss			-0.5	
Ground Ant. Gain			+39	
Polarization Loss			-1.0	
Cable Loss			-1.0	
Diplexer			-0.5	
Excess Noise Figure over ideal			-1.5	
Threshold S/N			-10	
Available Signal			-149.5 dbw	
Ideal 290° Recvr N_o			-204 dbw	
Excess Signal			+54.5 db	
Margin			+7 db	
Bandwidth			57.5 Kc	

Notes:

Service: 39 db Transmission

Vehicular Ant: Directional

Vehicular Power: 20 Watt Final

Ground Antenna: 39 db

CIRCUIT QUALITY CHART

	Carrier		Signal	
		Notes		Notes
Transmitter Power	13 dbw			
Carrier				
Signal			+13 dbw	
Mismatch Loss			-0.5	
Diplexer Loss			0	
Cable Loss			-0.5	
Ant. Pointing Loss			0	
Veh. Ant. Gain			+26 db	
Space Loss			-212	
Ant. Pointing Loss			-1.0	
Ground Ant. Gain			+53	
Polarization Loss			-1.0	
Cable Loss			-1.0	
Diplexer			-0.5	
Excess Noise Figure over ideal			-1.5	
Threshold S/N			-10	
Available Signal			-136 dbw	
Ideal 290° Recvr N_o			- 204 dbw	
Excess Signal			+68 db	
Margin			+7 db	
Bandwidth			1.25 Mc	

Notes:

Service: 52 db Transmission

Vehicular Ant: Directional

Vehicular Power: 20 Watt Final

Ground Antenna: 53 db

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	0 dbw			
Carrier	0 dbw			
Signal				
Mismatch Loss	-0.5			
Diplexer Loss	-0.5			
Cable Loss	-0.5			
Ant. Pointing Loss	0			
Veh. Ant. Gain	0			
Space Loss	-169			
Ant. Pointing Loss	-0.5			
Ground Ant. Gain	+39			
Polarization Loss	-1.0			
Cable Loss	-1.0			
Diplexer	-0.5			
Excess Noise Figure over ideal	-1.5			
S/N	-17			
Available Signal	-153 dbw			
Ideal 290° Recvr N_o	-204 dbw			
Excess Signal	+51 db			
Margin	+7 db			
Bandwidth	25 kc	(1)		

Notes:

Service: Near-Earth Transmission, Carrier Acquisition

Vehicular Ant: Omni

Vehicular Power: 1 Watt Final

Ground Antenna: 39 db

(1) It is assumed that the vehicle has an unlocked carrier stability of 1 part in 10^5 at 2.3 Kmc.

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	0 dbw			
Carrier	-20 dbw			
Signal			0 dbw	
Mismatch Loss	-0.5		-0.5	
Diplexer Loss	-0.5		-0.5	
Cable Loss	-0.5		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	0		0	
Space Loss	-169		-169	
Ant. Pointing Loss	-0.5		-0.5	
Ground Ant. Gain	+39		+39	
Polarization Loss	-1.0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5		-1.5	
Threshold S/N	-6.0		-10	
Available Signal	-162 dbw		-146 dbw	
Ideal 290° Recvr N_o	-204 dbw		-204 dbw	
Excess Signal	+42 db		+58 db	
Margin	+ 7 db		+ 7 db	
Bandwidth	+ 4 Kc		125 Kc	

Notes:

Service: Near-Earth Transmission

Vehicular Ant: Omni

Vehicular Power: 1 Watt Final

Ground Antenna: 39 db

CIRCUIT QUALITY CHART

	Carrier	Notes	Signal	Notes
Transmitter Power	+13 dbw			
Carrier	- 20 dbw			
Signal			+13 dbw	
Mismatch Loss	-0.5		-0.5	
Diplexer Loss	-0.5		-0.5	
Cable Loss	-0.5		-0.5	
Ant. Pointing Loss	0		0	
Veh. Ant. Gain	0		0	
Space Loss	-169		-169	
Ant. Pointing Loss	-0.5		-0.5	
Ground Ant. Gain	+39		+39	
Polarization Loss	-1.0		-1.0	
Cable Loss	-1.0		-1.0	
Diplexer	-0.5		-0.5	
Excess Noise Figure over ideal	-1.5		-1.5	
Threshold S/N	-6.0		-10	
Available Signal	-162 dbw		-133 dbw	
Ideal 290° Recvr N_o	-204 dbw		-204 dbw	
Excess Signal	42 db		+71 db	
Margin	+7 db		+7 db	
Bandwidth	+4 Kc		2.5 Mc	

Notes:

Service: Near-Earth Transmission
Vehicular Ant: Isotropic
Vehicular Power: 20 Watt Final
Ground Antenna: 39 db

APPENDIX B

Proposed System for Landing of the Apollo Vehicle

by

R. H. Vacca

1. Introduction

It is possible to obtain adequate closing range data and "on-course" indication for the Apollo vehicle for landing at land stations like Edwards A. F. B. by using only three ground stations. Figure B-1 shows one possible arrangement for these stations. At 300-nautical slant mile range from the A. F. B. closing range accuracies of about ± 6 nautical miles are possible. At 30 nautical miles slant range, the accuracy improves considerably and range can be determined to about ± 0.006 nautical miles. Bearing errors at these ranges can be held to less than 0.02 degrees. The primary limitation in obtaining these accuracies is the degree to which time differences can be measured and maintained within the entire system. We have assumed that time differences of ± 0.1 microseconds could be measured with suitable indicators from on-board the space vehicle.

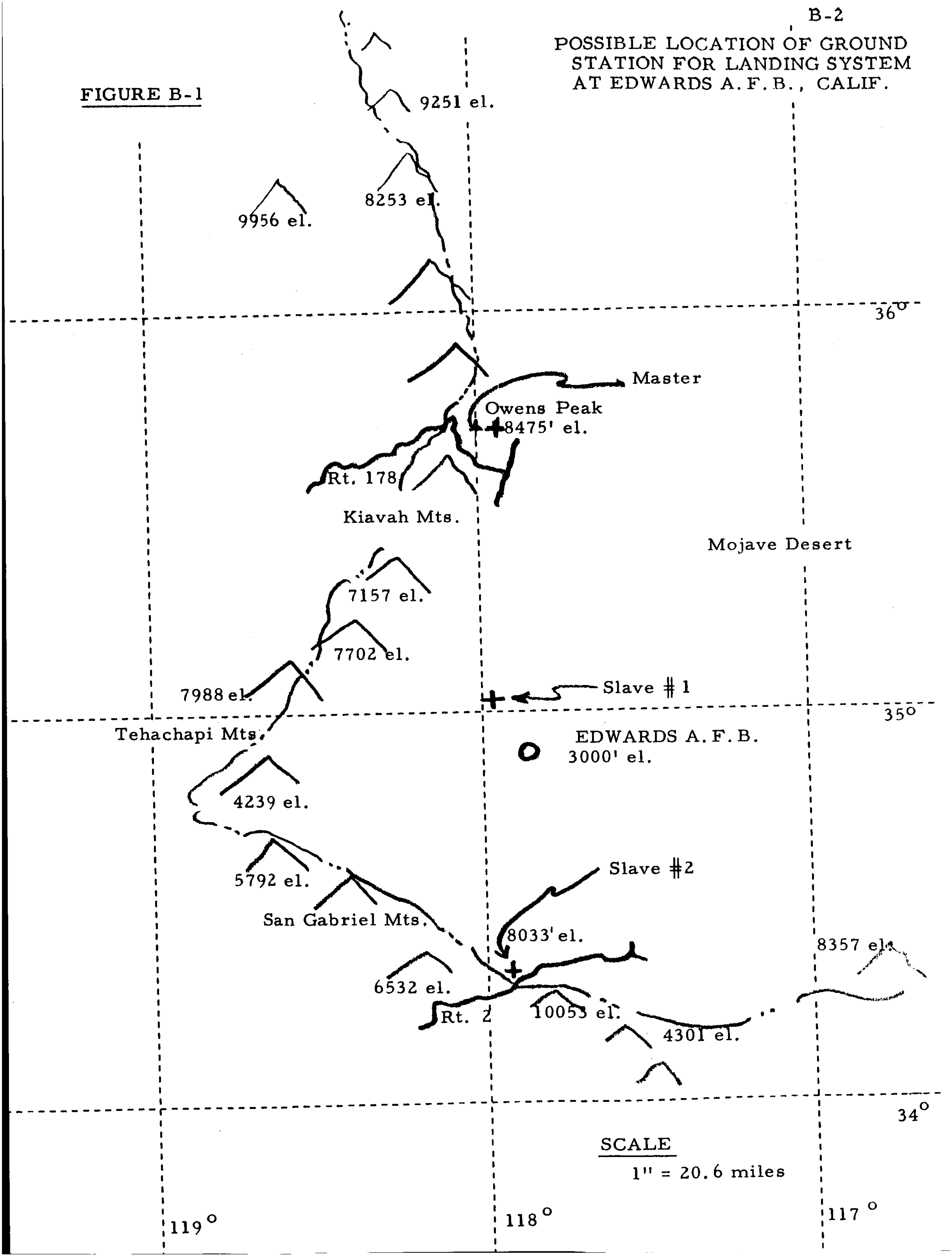
In order to make use of this ground system, no additional on-board equipment is required. We have assumed that S-band receivers, omni antennas and A-scope indicators that will be on-board for other functions of the space mission can also be used for the final landing operation at the prepared landing site at Edwards A. F. B.

2. System Description

References to Figures B-2, B-3, B-4 and B-5 give a good idea of the proposed landing system. All three ground transmitters emit a sequence of synchronized pulses. The master and slave station No. 2 are on the same frequency in "S" band. Slave station No. 1 is operating in the same band but distinct from the other two ground stations. This distinction is necessary in order to permit the dual sweep A-scope presentation shown in Figure B-3. This separation of the pulses from the two slave transmitters also allows the "on-board" digital computer to determine "closing-range" and "bearing" of the vehicle from the landing point in digital form.

FIGURE B-1

POSSIBLE LOCATION OF GROUND STATION FOR LANDING SYSTEM AT EDWARDS A.F.B., CALIF.

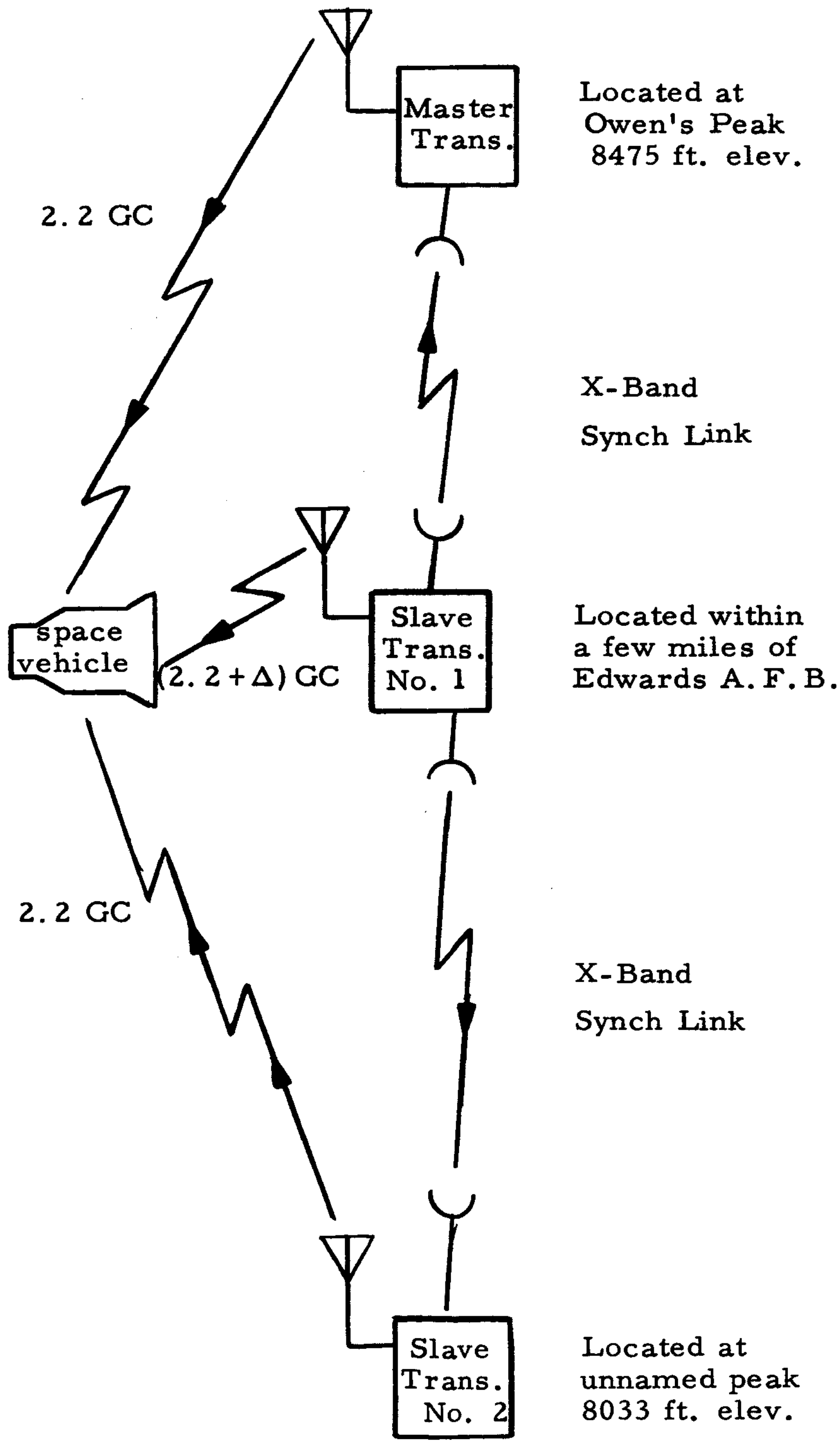


SCALE

1" = 20.6 miles

FIG. B-2

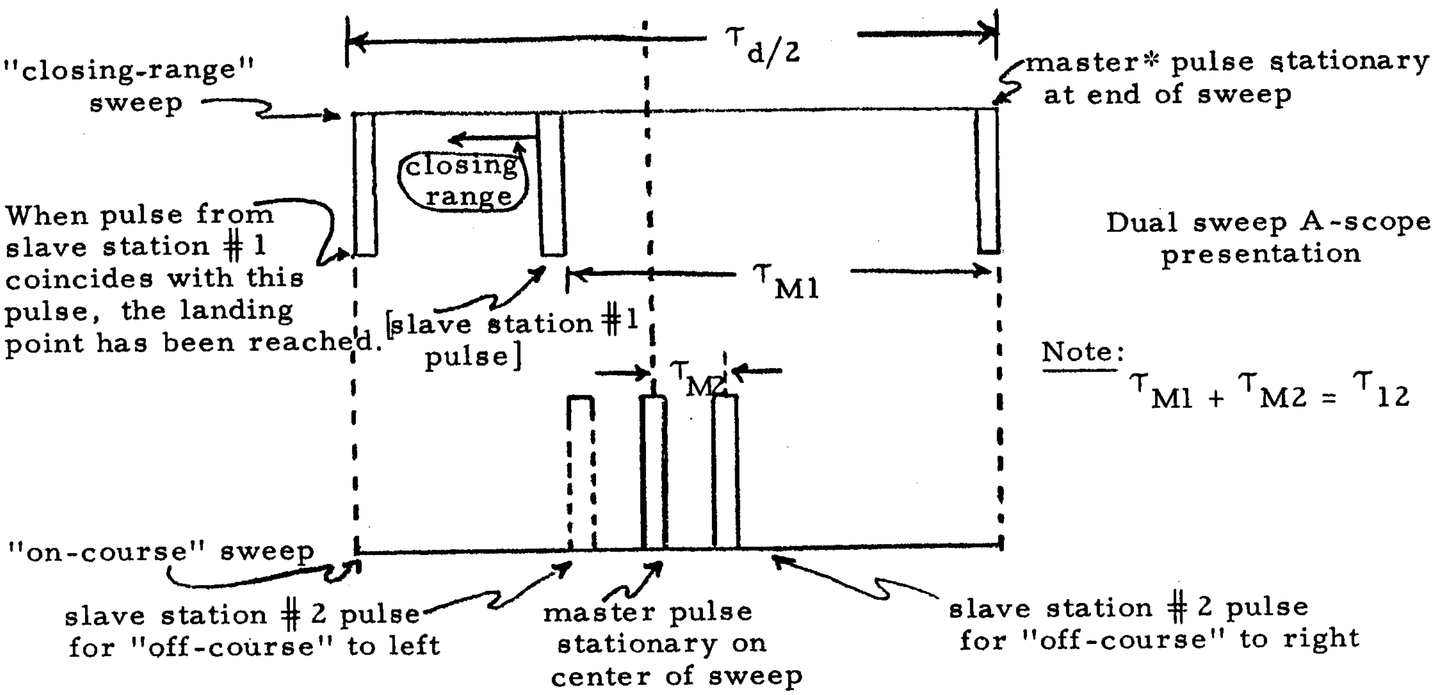
PROPOSED SYSTEM



NOTE: Each of the three transmitters emit a sequence of 1 μs 1000-watt peak pulses. X-band synchronization is required so that all these transmitters emit pulses at the same instant. The A-scope on board the vehicle is synchronized to the Master Transmitter only because it has a special code series of pulses for each burst instead of the single pulses being transmitted from the two slave stations.

FIGURE B-3

A-Scope Presentation on Board the Space Vehicle



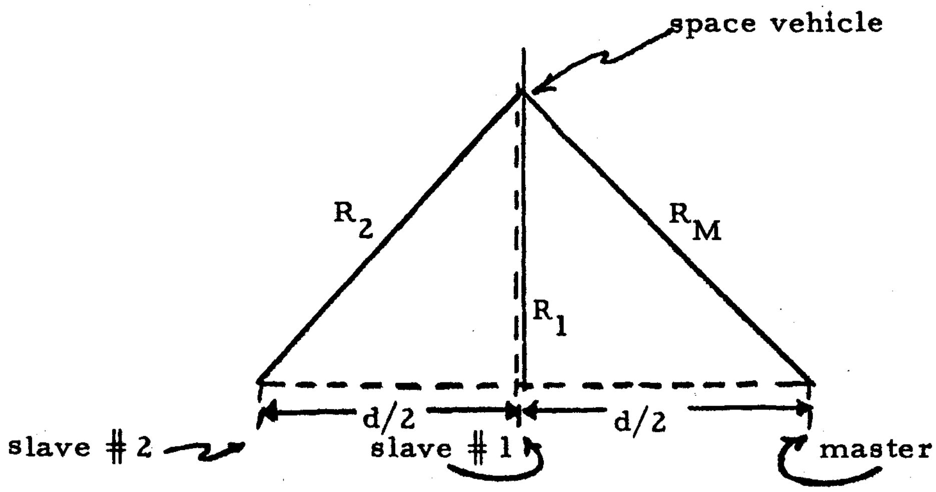
The "closing-range" and "on-course" pulses are on separate sweeps in order to avoid confusion in the region of overlap. The "closing-range" pulse is the one received from slave station # 1, and the "on-course" pulse pulse is the one received from slave station # 2.

Nøte: See figures 4 and 5 for definitions of $\tau_{d/2}$, τ_{M1} and τ_{12}.
$\tau_{M2} \triangleq$ time difference between pulses received at the vehicle from the master and slave station # 2.

* The master pulse is shown as one pulse on the two sweeps. It is actually a marker pulse derived from the actual short code group master pulse.

FIGURE B-4

Diagram used in the on-course range error calculations.



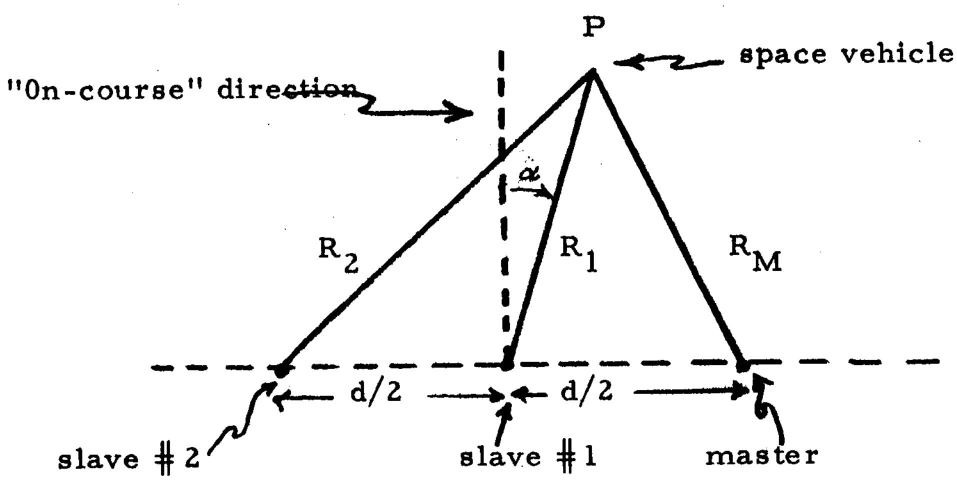
$$R_1 = \frac{c}{2} \; \frac{(\tau_{d/2})^2 - \tau_{M1}^{\;2}}{\tau_{M1}}$$

Where $\tau_{d/2}$ = time required for pulse to travel distance d/2 and τ_{M1} = time difference between pulses received at the vehicle from the master and slave station # 1.

This value for R_1 (closing range) assumes the space vehicle is on-course. See Fig. 5 for the case when the space vehicle is off-course.

FIGURE B-5

Diagram used to compute the closing range and bearing when the vehicle is "off-course."



τ_{12} = time difference between pulses received at the vehicle from slave stations # 1 and # 2.

τ_{M1} and $\tau_{d/2}$ have already been defined in Figure 4.

note:

$\tau_{12} - \tau_{M1} = \tau_{M2}$

$$R_1 = c \; \frac{\tau_{d/2}^{\,2} - \dfrac{(\tau_{12}^{\,2} + \tau_{M1}^{\,2})}{2}}{\tau_{12} + \tau_{M1}}$$

$$\sin\alpha = \frac{c}{d}\left[\frac{1 + \dfrac{\tau_{12}\tau_{M1}}{\tau_{d/2}^{\,2}}}{1 - \dfrac{1}{2}\,\dfrac{\tau_{12}^{\,2} + \tau_{M1}^{\,2}}{\tau_{d/2}^{\,2}}}\right](\tau_{12} - \tau_{M1})$$

and for the "near-on-course" condition

$$\alpha \cong \frac{c}{d}\sqrt{1 + \left(\frac{d/2}{R_1}\right)^2}\left(\tau_{12} - \tau_{M1}\right) = \frac{c}{d}\left[\sqrt{1 + \left(\frac{d/2}{R_1}\right)^2}\,\right]\tau_{M2}$$

where we find this last result convenient for computing the magnitude of α for small perturbations from the "on-course" condition as a function of R_1.

Pulse coding is only required for the pulses transmitted from the master station. This is required in order that the two A-scope sweeps be synchronized to the master pulse and not to the pulses taken from either slave station. Pulse coding will not be required for either slave station.

The effectiveness of this system in determining "closing-range" without ambiguities and uncertainties depends on keeping the vehicle "on-course". Thus, before the pilot relies on his "closing-range" display, he should be "on-course" as determined from the "on-course" display. When the fixed central master pulse time marker coincides with the pulse received from slave station No. 2, the pilot can be sure he is "on-course" (see Figure B-3). The error analysis made in the following section shows that it is possible to determine the "on-course" condition well inside of the region where uncertainties in range do not arise. There is no ambiguity in the "on-course" condition, because the pulses from the master station and the slave station No. 2 arrive at the vehicle at the same time only along the "on-course" line. Thus, a measurement of τ_{M2},* either on the A-scope "on-course" display or by use of the digital computer will quickly enable the pilot to determine if he is "on-course" well enough to be able to rely on his "closing-range" indicator.

The A-scope "closing-range" presentation yields incorrect results for some special cases when the vehicle is "off-course". For example, the time interval τ_{M1} ** will always be zero along one line parallel to the "on-course" direction. This line is the perpendicular bisector of the line connecting the slave station No. 1 and the master station. Thus, a flight path along the perpendicular bisector course would indicate no change in the "closing-range". However, the "on-course" display would show that the vehicle was "off-course" and reveal to the pilot that his vehicle was following a path that gave incorrect information for "closing-range".

It may be possible to resolve these uncertainties and ambiguities in "closing-range" data for the "off-course" condition by making use of the "on-board" computer. In any case, however, the landing system will always provide unambiguous "on-course" sensing and also yield accurate "closing-range" data for the "near-on-course" condition.

---

* τ_{M2} is the difference in time of arrival at the vehicle of pulses from the master station and the No. 2 slave station.

** τ_{M1} is the difference in time of arrival at the vehicle of pulses from the master station and slave station No. 1. (also see Figures B-3 and B-5)

3. Error Analysis

The equation for the "closing-range" for the "on-course" condition is given in Figure B-4. This equation can be rewritten in the following way.

$$R_1 = \frac{c}{2} \frac{(\tau_{d/2} - \tau_{M1})(\tau_{d/2} + \tau_{M1})}{\tau_{M1}}$$

In order to obtain this relation in differential form, we first take the ln of all terms.

$$\ln R_1 = \ln \frac{c}{2} + \ln (\tau_{d/2} - \tau_{M1}) + \ln (\tau_{d/2} + \tau_{M1}) - \ln \tau_{M1}$$

Now by differentiation, we obtain:

$$\frac{\Delta R_1}{R_1} = \frac{\Delta c^*}{c} + \frac{\Delta(\tau_{d/2} - \tau_{M1})}{\tau_{d/2} - \tau_{M1}} + \frac{\Delta(\tau_{d/2} + \tau_{M1})}{\tau_{d/2} + \tau_{M1}} - \frac{\Delta\tau_{M1}}{\tau_{M1}}$$

The Δ terms can have + or - values depending on the direction of the errors. Thus, for the maximum value of the error in range R_1 we make each percentage error term have the same sign, thus:

$$\left.\frac{\Delta R_1}{R_1}\right|_{max} = \pm\left[\left|\frac{\Delta c}{c}\right| + \left|\frac{\Delta(\tau_{d/2} - \tau_{M1})}{\tau_{d/2} - \tau_{M1}}\right| + \left|\frac{\Delta(\tau_{d/2} + \tau_{M1})}{\tau_{d/2} + \tau_{M1}}\right| + \left|\frac{\Delta\tau_{M1}}{\tau_{M1}}\right|\right]$$

A sample calculation of $\left.\frac{\Delta R_1}{R_1}\right|_{max}$ for the 30 nautical miles "closing-range" yields:

$$\left.\frac{\Delta R_1}{R_1}\right|_{max} = \pm\left[10^{-6} + \frac{10^{-7**}}{(258-133)10^{-6}} + \frac{10^{-7}}{(258+133)\,10^{-6}} + \frac{10^{-7}}{133\text{x}10^{-6}}\right]$$

$$'' \quad = \pm\, 10^{-6} + 800\text{x}10^{-6} + 256\text{x}10^{-6} + 753\text{x}10^{-6}$$

$$'' \quad = \pm\, 0.0018$$

or $\Delta R_{1max} = \pm\, 0.054$ nautical miles at $R_1 = 30$ nautical miles.

A similar calculation for $R_1 = 300$ nautical miles yields:

$$\Delta R_{1max} = \pm\, 5.8 \text{ nautical miles}$$

Another point of interest in this error analysis is the relation between the vehicle bearing accuracy and the minumum discernible time difference that can be measured. The relation of α given in Figure B-5 is useful for determining the magnitude of α for small perturbations from the "on-course" condition as a function of range R_1.

---

* The $\frac{\Delta c}{c}$ term represents the extent to which the speed of light is unknown.

** We have assumed the min. discernible time diff. = 0.1μs.

Thus, at R_1 = 30 nautical miles

$$\alpha \cong \frac{c}{d} \sqrt{1 + \frac{(d/2)^2}{R_1}}\ \tau_{M2} \quad \text{(see Figure B-5)} \qquad d = 84 \text{ nautical miles}$$

$$\alpha \cong \frac{162000}{84} \sqrt{1 + \frac{(42)^2}{30}}\ (10^{-7}) \qquad c = 162000 \text{ nautical miles/sec.}$$

α = 3.32 x 10^{-4} radians or 0.019 degrees; c = vel. of light

a similar calculation at R_1 = 300 nautical miles yields:

$\cong$ 0.011 degrees

Other calculations were also made to determine the effect of noise on the range and bearing accuracy. It was found that for a 15 db signal-to-noise ratio, the inaccuracy due to noise was negligible compared to the accuracy with which time differences could be measured. At the maximum range of 300 nautical miles, the 15 db signal-to-noise ratio was achieved with peak power outputs of 1000 watts and one microsecond pulses. Antenna gains for both ground and vehicle were assumed to be zero db. Total receiver noise temperature was set to 828°K.

4. Conclusions

The landing system just described should be relatively easy to implement. All three ground stations could each be contained within a small trailer. Antennas for each station could be mounted on the trailer roof. Two-foot diameter parabolas would be adequate for the X-band synchronization links. The antenna for the S-band link to the space vehicle could be a simple stacked array of dipoles; quite similar to the television transmitter arrays. Instead of 360 - degree azimuth coverage, however, about 120° would be satisfactory.

A desirable feature of the system is that no additional equipment will be required on-board the space ship. The omni antenna, S-band receiver, and A-scope indicator will already be on-board for other functions.

Pulses from the slave station No. 1 will be prevented from reaching the space ship at ranges much greater than 300 nautical miles because of the mountains to the West. Ranges greater than 300 nautical miles are possible, however, if the master and slave station No. 2 peak power outputs are increased to, say, 10,000 watts. In this case, however, only "homing" will be possible and "closing-range" information will not be made available because of the horizon limited signals from the central slave station No. 1. When the space ship is within 300 nautical miles* of the slave station No. 1, however, it will, of course, be possible to have closing-range information as well.

Since this system is restricted to yielding information on slant range and bearing, it will be necessary to use the "on-board" altimeter to determine the altitude of the vehicle. A complication arises in the use of the "on-board" altimeter because of the non-directional properties of the available omni antenna. However, this difficulty may be resolved by determining the altitude from the leading edge of an extended time return. Any aircraft in the vicinity will appear as point targets and should be easily discernible from a return from an extended target such as the surface of the earth.

Another important point is that it is not essential that the slave station No. 1 be located on the center of the imaginary line connecting the two outside stations. The system accuracy may be reduced by locating the central station in some other place, and the computing may become more complicated, but the system will still perform its intended function.

Finally, in computing the range accuracies we have assumed it will be possible to easily measure time differences of about 0.1 microsecond. If this time measurement accuracy cannot be easily obtained, the range and bearing accuracy will be degraded in direct proportion.

* A 30-nautical mile altitude has been assumed for space ship at 300 nautical miles.

APPENDIX C

Rendezvous Terminal Sensing

by

A. J. Morency and R. H. Vacca

1. Requirements for Radar Measurements During the Terminal Phase of Rendezvous

It is assumed that the terminal phase starts with the maneuvering vehicle in the vicinity of the orbiting vehicle with approximately matched velocities. Several studies have been made of possible terminal guidance techniques. These are very heavily conditioned by the assumption made by the authors about the available propulsions, the available sensors, and the permissible complexity of the guidance doctrine.

The Apollo vehicle, as presently envisioned, will be equipped with an on-board propulsion system with at most two levels of thrust and with restart capability. The on-board computer will be reasonably fast and have (because of the lunar mission) considerable capacity. This suggests a fairly sophisticated guidance doctrine.

In view of the difficulty of launching at a precise time, and in order not to be limited by the sensing capability, the maneuvering vehicle should have a radar capable of measuring the relative position (two angles and range) out to 100 nautical miles when the orbiting vehicle is equipped with a beacon and to at least 25 nautical miles skin tracking. The angle measurements might be supplemented at close range by optical measurements to avoid the necessity of a large antenna or beam splitting techniques. Range-rate would be desirable, but may be obtained by differentiating the range measurements if adequate precision is available.

2. Skin Ranging Between Space Vehicles

A. 2.3 GC

1. 2.30 GC/s frequency
2. 100 watts peak power, 20 watts average
3. Pulse length adjustable 1 to 300 microseconds, with pulse repetition frequency limited by average power and ambiguous range considerations.

4. Four foot parabolic antenna
   a. 26.5 db gain (55 per cent effective)
   b. 8^{o} beamwidth (1/2 power)
5. System noise temperature = $828^{o}K$
   a. 3 db noise figure + 1.5 db loss from receiver to antenna
      528^{o} K noise temperature referred to the antenna
   b. antenna looks at external 300^{o} K noise temperature
6. On transmission 1.5 db loss between transmitter and antenna
7. σ = 100 square meter target area
8. (S/N) $\cong$ 15 db; P_d = 95 per cent; $P_{fa} = 10^{-9}$ for single pulse detection

The following table was prepared using the above data:

τ	R	$\frac{C\tau}{2}$	δ_r
μs	meters	meters	meters
1	13,500	150	2.8
10	24,000	1500	28
100	42,700	15000	280
300	56,000	45000	840

Pulse lengths greater than about 300 microseconds cannot be used because the reflected pulse will overlap in time with the transmitted pulse.

B. C-Band Altimeter
1. 5.5 G C/s frequency
2. 40 KW peak power
3. Pulse length = 1 microsecond
4. 4-foot parabolic antenna
   a. 34.3 db gain (55 per cent effective)
   b. 3.3^{o} beamwidth (1/2 power)
5. System noise temperature = $1200^{o}K$
   a. 4 db noise figure receiver + 2 db loss from receiver to antenna, $900^{o}K$ noise temperature referred to the antenna
   b. antenna looks at external $300^{o}K$ noise

6. On transmission 2 db loss between transmitter and antenna
7. σ = 100 sq. meter target
8. (S/N) ~ 15db; P_d = 95 per cent; $P_{fa} = 10^{-9}$ for single pulse detection
9. Range = 79, 400 meters
10. δ_r = 2.80 meters

Conclusions:

Ranging between vehicles is limited to about 56, 000 meters (28 nautical miles) for the 100 watt peak power limit at 2.2 GC/s. Furthermore, at this range the accuracy is about 840 meter (~0.5 nautical miles). Better accuracies with this system can be obtained by reducing the transmitter pulse width, but at the same time reducing the range (see table on page C-2). Greater range is available with high power C-band equipment used for rendezvous ranging.

APPENDIX D

The Influence of the Environment of Apollo Design from the Radar-Communication Viewpoint

by

W. F. Higgins

1. Some Environmental Considerations in the Selection of an Operating Frequency for Apollo

The antenna noise contributions of environmental, galactic, and discrete sky sources have been studied for the Apollo mission as a function of frequency.[1] The aim of this documentation has been to determine what frequencies, based on noise considerations only, should be recommended for the Apollo mission. The environmental noise contributions arise from the ground, atmosphere, and rainfall. The galactic contributions arise principally from the dense star background in the Milky Way. Discrete sky sources include the radio stars, the sun, and the moon. The noise received by the radar antenna which is generated by the sun, the principal radio stars, and the general galactic background decreases rapidly with increases in radar frequency. The noise contributions from the earth and moon appear to be (from the available evidence) independent of frequency over the radar frequency band. The noise contribution due to the environmental factors of oxygen, water vapor, or rain increases rather rapidly for frequencies above about 10 kMc. When all factors are considered, it appears that a frequency in the lower kMc band should be recommended for the Apollo lunar mission although it should be emphasized that no sharp boundaries exist between the recommended frequency band and frequencies immediately exterior to this band. During lunar missions, the noise contribution from the moon, for a fixed receiving dish size, is important in determining the best operating frequency when the space vehicle is in the proximity of the moon. Figure D-1 shows the antenna temperature as a function of frequency when the moon is in the mainlobe of an 80' paraboloidal dish. The antenna temperature is given in degrees Kelvin. Figure D-2 shows

1. W. Higgins, "The Influence of the Environment on Apollo Design from the Radar-Communication Viewpoint", Lincoln Laboratory Report 43G-0001, July 1961.

that the noise minimum occurs at a frequency of about 2 kMc when the antenna diameter is reduced to 20 feet. Figure D-3 shows the signal-to-noise ratio for a point source having an antenna temperature of 50°k at 2000 Mc for a 20-foot paraboloidal dish for different dish sizes as a function of frequency when the moon is in the mainlobeof the receiving antenna.

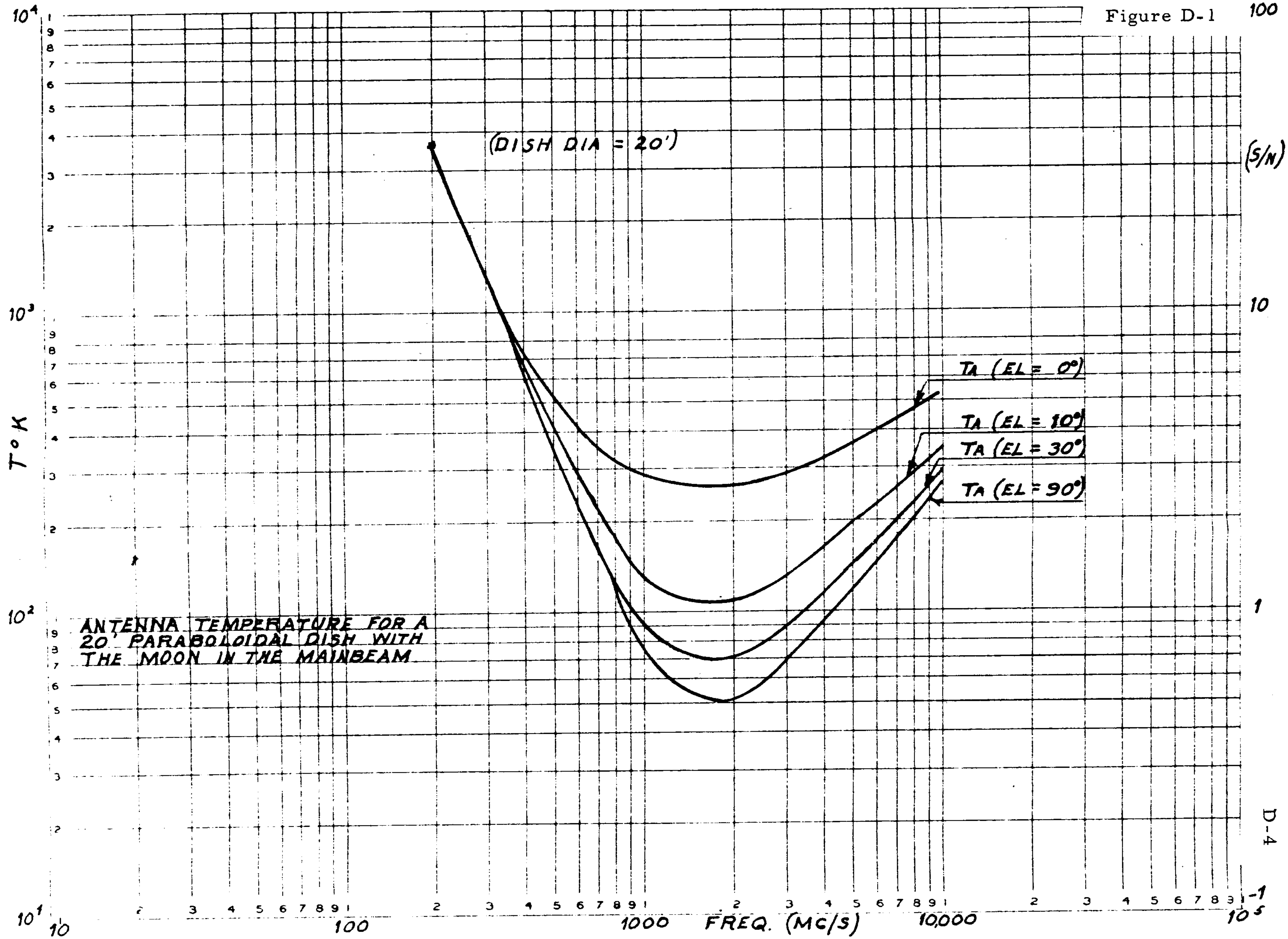
2. Some Basic Limitations on Radar Measurement Accuracy

A study has been made in Reference 1 of the basic limitations on radar measurement accuracy imposed by the environment for frequencies in the kMc region and the uncertainty in the velocity of light. The range measuring accuracy of the deep space network is limited principally by the uncertainty in the velocity of light. Standard deviations in angular refraction due to variations in the refractivity profile from a standard profile also generate appreciable range error at the lower kMc end of the frequency band considered. More detailed atmospheric data would allow the error in range to be reduced but since the uncertainty in the velocity of light is about 1 part in 10^{6}, the portion of the range error due to atmospheric influences is negligible in comparison to the errors produced by the uncertainty in the velocity of light at lunar ranges and atmospheric corrections are scarcely warranted for range measurements for this case. When a standard refractivity profile is used for angular corrections and the surface index of refraction is measured at the instant of angle measurement, the elevation angle can be corrected to the order of a few seconds of arc (15 microradians). Experimental evidence indicates that it should be possible to measure angles to the order of about $\pm$ 50 microradians in the kMc frequency region. Higher angular measurement accuracy is available at high elevation angles. The lower bound on angular accuracy is generated by scintillation noise which may be of the order of 100 microradians at an elevation angle of 1° (at C-band). The scintillation error decreases rapidly with increases in the elevation angle. It is obviously true that better meterological data along the ray path can reduce the angle measurements to the accuracy produced by scintillation alone. It is also clear that such an eventuality is economically unfeasible. Range rate accuracy is limited by the uncertainty in the index of refraction at the space vehicle, angular uncertainty, and rapid time variations in the refractivity along the ray path. The survey performed in Reference 1 has shown that the doppler accuracy has a strong elevation angle dependence. At the lower elevation angles, doppler can be measured to about 1 ft/sec. At zenith it should be possible to measure doppler to .01 ft/sec. if computations are made to compensate for refraction.

For vehicles within the atmosphere, the range error is due principally to refraction and the range rate error is also affected by the uncertainty in the index of refraction at the location of the vehicle. Although it is quite difficult to state what the limitations on accuracies are, without getting involved in a detailed explanation of the types of corrective procedures and measurements made and the elevation angles, time of day, etc., it is possible to state some average design goals which are reasonable design goals for the Apollo mission. These design goals are based only on the accuracy limitations imposed by the environment and the uncertainty in the velocity of light.

A.	Deep space net	(S-band)
	Range accuracy	$\pm$ 100 ft. for range of 1000 nautical miles
		$\pm$ 5000 ft. at lunar distances
	Angle accuracy	$\pm$ 50 microradians
	Range rate accuracy	$\pm$ .1 ft/sec
B.	Tracking network	(S-band or C-band)
	Range accuracy	$\pm$ 25 ft.
	Angle accuracy	$\pm$ 50 microradians
	Range rate accuracy	$\pm$ .1 ft/sec

Figure D-1



(DISH DIA = 20')
TA (EL = 0°)
TA (EL = 10°)
TA (EL = 30°)
TA (EL = 90°)
ANTENNA TEMPERATURE FOR A 20' PARABOLOIDAL DISH WITH THE MOON IN THE MAINBEAM
T °K
(S/N)
FREQ. (MC/S)
10
100
1000
10,000
10^5
10^1
10^2
10^3
10^4
1
10
100
10^{-1}

Figure D-2

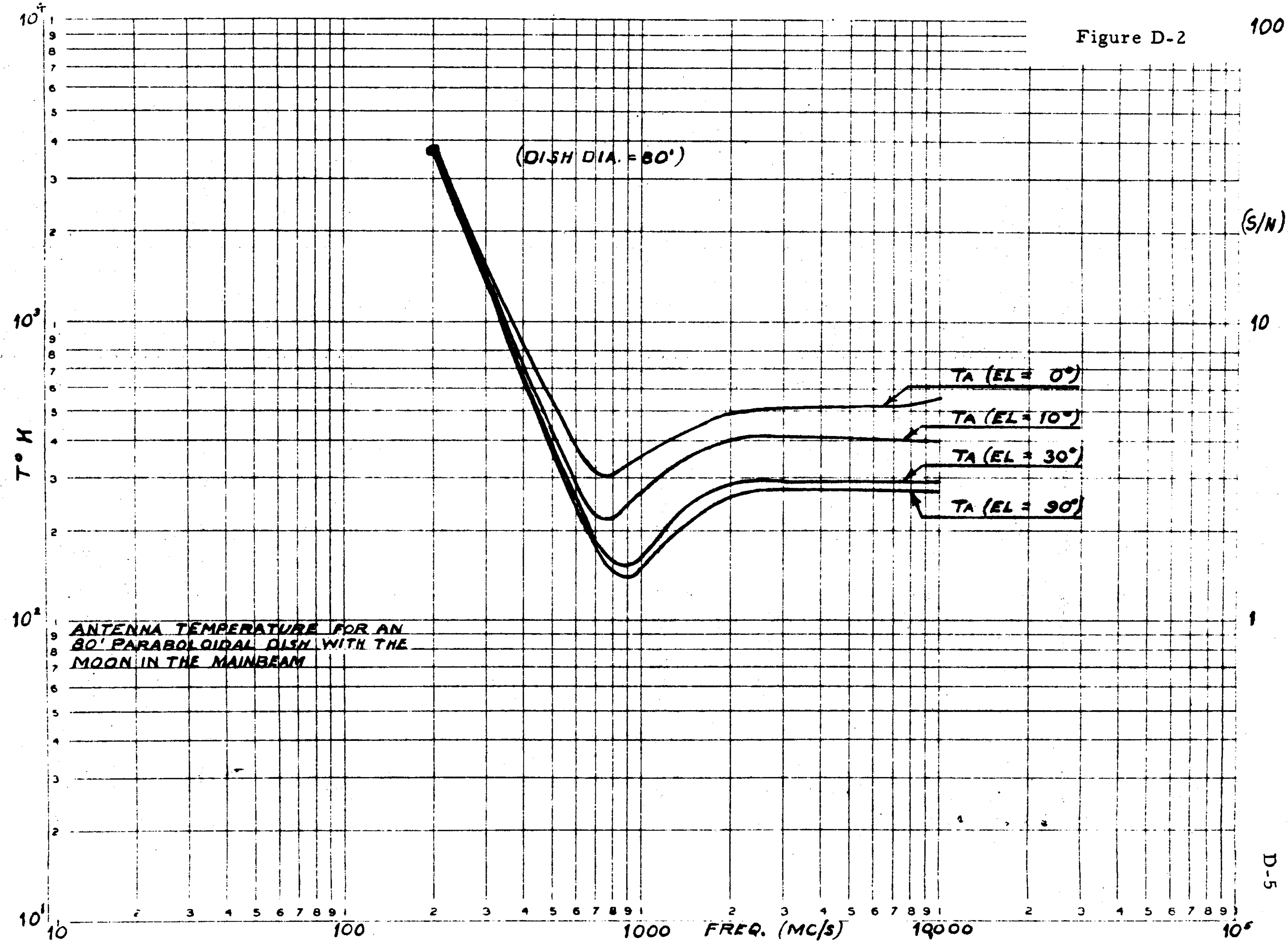
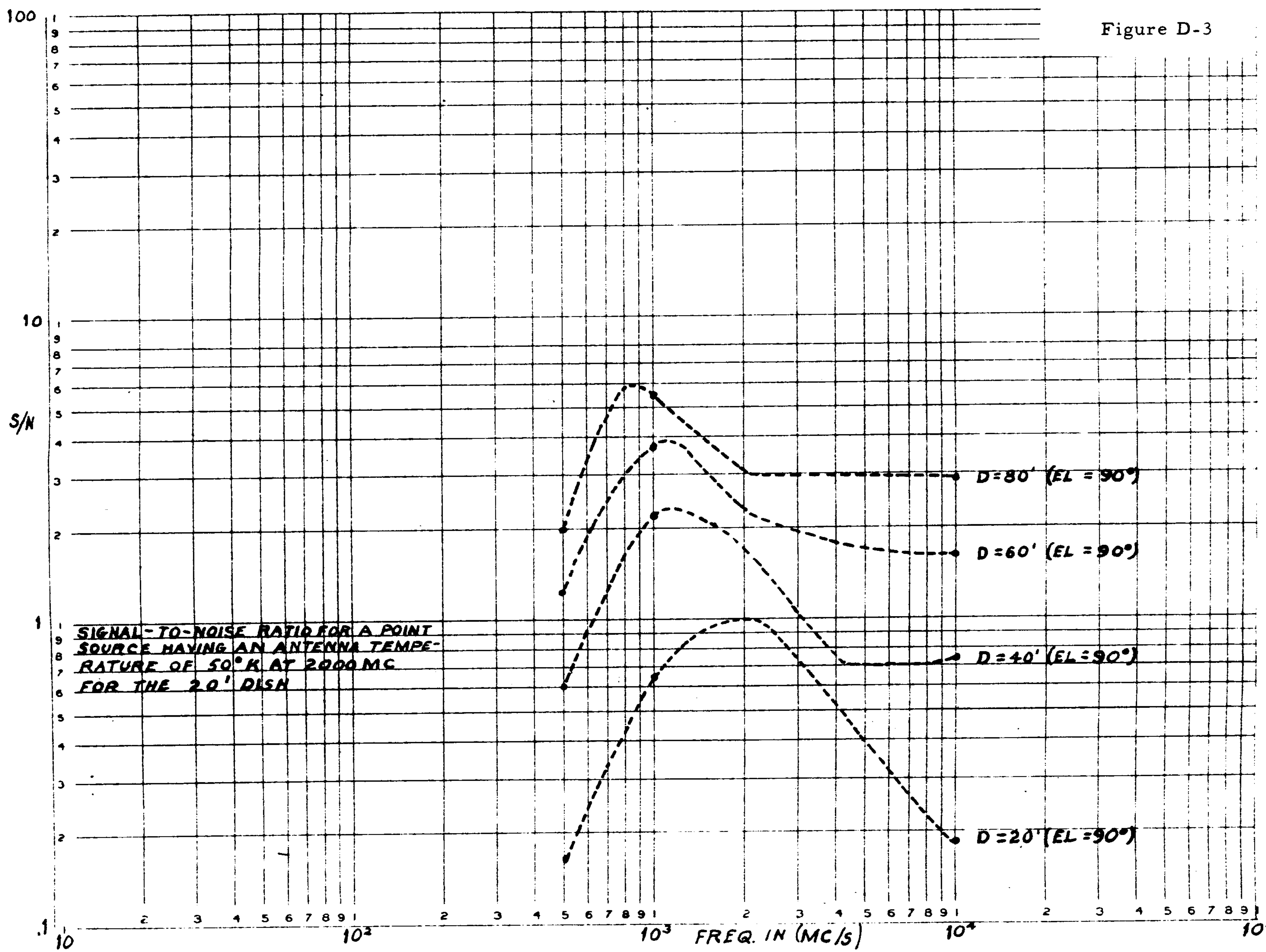

(DISH DIA. = 80')
TA (EL = 0°)
TA (EL = 10°)
TA (EL = 30°)
TA (EL = 90°)
ANTENNA TEMPERATURE FOR AN
80' PARABOLOIDAL DISH WITH THE
MOON IN THE MAINBEAM
T° K
(S/N)
FREQ. (MC/s)
10
100
1000
10000
10^4
10^3
10^2
10^1
10^5
100
10
1

Figure D-3


100
10
S/N
1
.1
SIGNAL-TO-NOISE RATIO FOR A POINT SOURCE HAVING AN ANTENNA TEMPERATURE OF 50°K AT 2000 MC FOR THE 20' DISH
D=80' (EL = 90°)
D=60' (EL = 90°)
D=40' (EL=90°)
D=20' (EL=90°)
10
10^2
10^3
10^4
10^5
FREQ. IN (MC/S)

APPENDIX E

A Coherent Pulse Code S-Band Radar for Altimetry, Rendezvous and Space Exploration

by

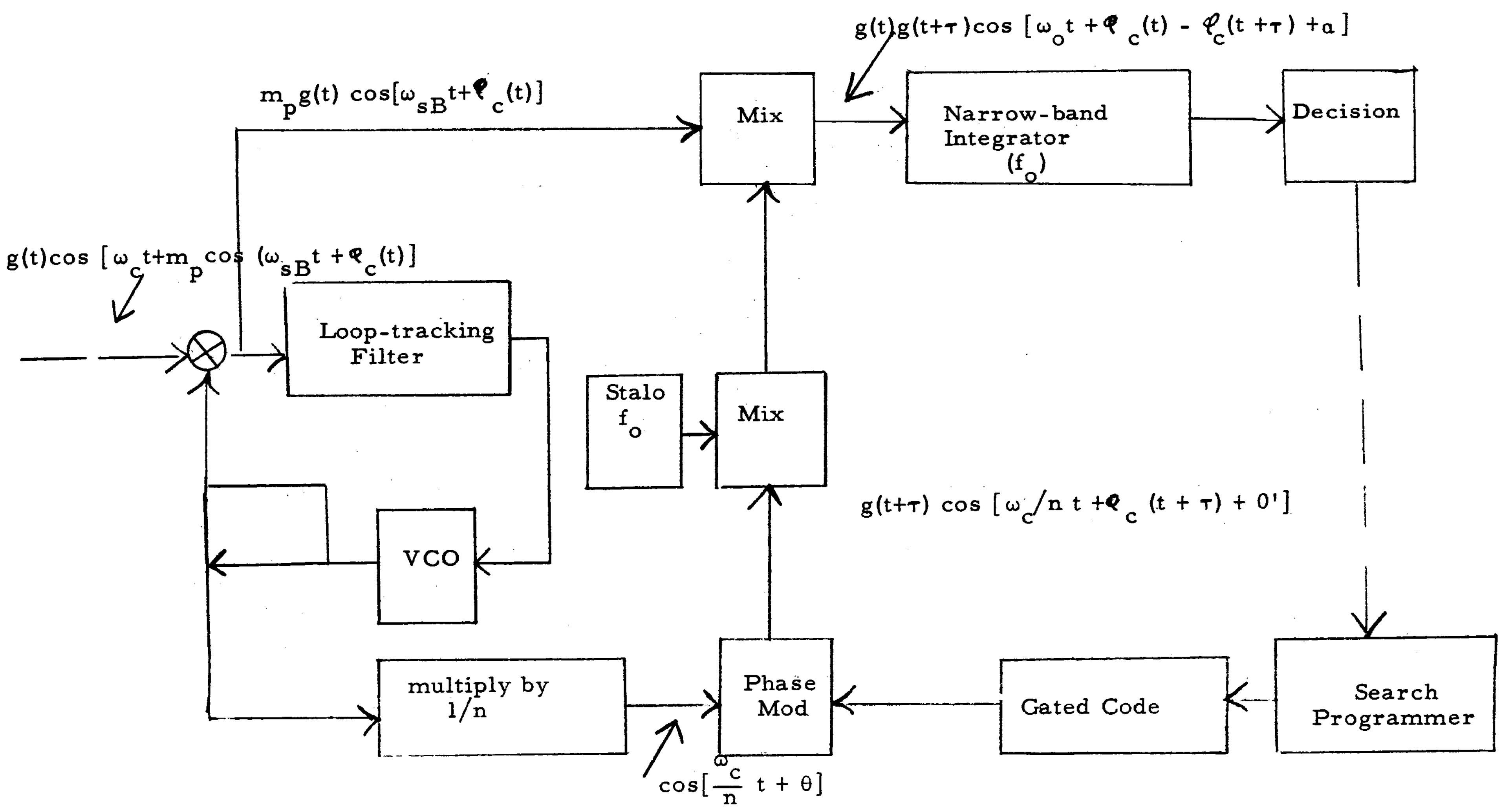
W. F. Higgins

A motivation exists for prescribing a unified spacecraft system for Apollo. This motivation arises from a desire to minimize the number of space capsule equipments and operating frequencies as well as the equipment weight. It appears logical to make use of elements of the S-band equipment of the DSIF type for altimetry, rendezvous and space exploration if this equipment can be modified to accommodate these modes of operation. One must then decide, based upon the performance of the postulated S-band altimetry and rendezvous system, whether it is competitive with other methods of performing the same function. The first problem to be considered is lunar altimetry.

Consider the functional system of the receiver shown in Figure E-1. We are considering the use of a gated phase coded ranging system for lunar altimetry. This system makes use of some features of the DSIF spacecraft equipment for lunar altimetry. The binary code phase modulates the transmitted waveform periodically. The pulses of the carrier, phase modulated by a maximal length binary shift register code, are transmitted at a repetition period determined by the gating function g(t). The receiver will phase lock to the gated carrier if the modulation index, m_p, is restricted to a small value. By requiring $\frac{\omega_c}{n} = \omega_{SB}$, it is possible to use a narrowband integrator for decision making. The operation of the receiving system should be obvious from the functional diagram of Figure E-1. The lock-on procedure will require a time of $\frac{1}{\Delta f_o}$ where Δf_o is bandwidth of the narrowband integrator. The code length is restricted by the requirement for unambiguous range and reasonable acquisition time. For a range of 1000 miles, the code period could be a minimum of .01 second. The narrowband integrator for the minimum code period would then have a 3 db bandwidth of 100 cps. For a duty cycle of 10 per cent, the number of elements in the code would be 100 if each code element were 10 microseconds in duration. The search time for lock-on

COHERENT PULSE CODE RECEIVER

FIGURE E-1



in this case will be a minimum of 10 seconds. If each code element were 1 microsecond in duration, a 1000 element code could be used. In this case, a search time of about 2 minutes is required. Once acquisition is obtained, track can be accomplished by forming an error signal at the output of the narrowband integrators (three are required to form the error function but only one is shown). The code length and the narrowband integrator bandwidth can be programmed as a function of the unambiguous range to the target.

The system of Figure E-1 allows the use of narrowbanding and an increase in system sensitivity over what is available with a conventional pulsed system.

Several problems need to be examined in minute detail for the scheme of Figure E-1. These problems arise from the fact that the moon and other solar bodies are large spherical targets with non-smooth surfaces and the echo returns exhibit phase jitter and a time extension which can be troublesome in the ranging operation particularly if the antenna beamwidth or the distance of the space vehicle from the target is large. Blind spots also can occur in range during acquisition procedures if the target echo returns occur at the time that the transmitter is gated on. The latter problem has been solved in pulse doppler seekers by jittering the prf. A similar solution would apply to the system of Figure E-1. The effect of phase jitter places a lower bound on the phase tracking loop bandwidth. The magnitude of the effect of phase jitter on the final integration process is not known precisely at this time but it clearly depends on target characteristics.

The sensitivity of the receiver will depend on the bandwidth of the narrowband integrator. Let us assume the 3 db bandwidth of the integrating filter is 100 cps. Assuming an antenna temperature of $820^{o}K$, the sensitivity of the receiver is -180 dbm. The peak power required for ranging on the lunar surface with a 1000-element code from a distance of 2000 nautical miles will be of the order of 10 watts total power of which the range coded sub-carrier will require 1 watt.

APPENDIX F

Recovery Aids

by

R. H. Vacca

One form of HF beacon that may be used in the recovery phase of the Apollo program delivers 5 watts at 8.3 mc/s. We have arbitrarily assumed a maximum range of 1600 KM from the HF direction finding stations. For 1-hop-F_2 propagation the received signal has been computed to be 7 db below 1 μv/meter. In the presence of atmospheric noise, the required signal strength for 90 per cent voice intelligibility (6 Kc/s bandwidth receiver) should be + 17db above 1 μv/meter. Thus, it appears that voice communication at ranges of 1600 KM is not feasible since the required received signal is (17+7) = 24 db above the value required. On the other hand, if manual CW telegraphy is transmitted and the rec.BW is still 6 Kc/s, the required signal for intelligible reception 90 per cent of the time is 0 db above 1 μv/meter. It thus appears that even for manual CW telegraphy 7 db more signal is still required. If the bandwidth of the receiver is now reduced to 600 c/s, the receiver atmospheric noise* reduced by 10 db. In this case the received signal is now 3 db above the required signal for 90 per cent intelligibility of manual CW telegraphy. But 3 db is hardly a safe margin since the lobing effects and the efficiency of the vertical radiator have not been considered. If a steady CW signal is transmitted, the BW could be reduced to perhaps 60 c/s and a 13 db margin would be obtained. This margin might be just large enough to compensate for the possibility of a deep null in the radiation pattern of the vertical radiator. A 60 c/s BW receiver implies that the stability of the beacon transmitter and the HF receiver be adequate.

Briefly we can say that at 1600 KM ranges, the 5-watt beacon transmitter is very marginal even for the 60 c/s narrow band case. All that could be accomplished with this bandwidth is very slow speed telegraphy and CW carrier emission for HF direction finding.

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* Assumed atmospheric noise spectrum is essentially flat over band.

When the range is reduced to 1200 KM, the 1-hop-F_2 propagation produces a signal level that is 9 db above that produced at the 1600 KM range. At 800 KM range there is a 16 db improvement in received signal, and at 400 KM there is a 23 db gain over the value obtained at 1600 KM.

For distances less than 400 KM, the received signal is limited primarily by the very deep null that exists near the vertical of the radiation pattern of the vertical radiator. This is not too serious, however, because at these close ranges it will be possible for the Super Sarah beacon signal to be received by at least one of several search aircraft.

The above calculations were based on the data given in National Bureau of Standards Circular 462, entitled "Ionospheric Radio Propagation". In computing the absorption index for the ionosphere, several factors were assumed. The seasonal variation factor used was 1.15 corresponding to the month of April, (see table 7.1 - p. 112). The solar activity factor Q was computed to be 1.56 assuming a sunspot number R equal to 112. Figure 512 on page 59 indicates that this is close to the average of the maximum value, (which occurs every 11 years). The average diurnal variation factor K was found from figure 7.37 on p. 139 for the Edwards A.F.B. area at 1500 GMT to be 0.66.

In determining the received signal for the 1-hop-F_2 propagation modes at various ranges, the figures used were 7.13, 7.16, 7.20 and 7.24. The minimum required signal in the presence of atmospheric noise was found from figures 8.5, 8.6, 8.7, 8.8, 8.9 and 8.10. At 8.3 mc/s cosmic noise is small compared to atmospheric noise.

If the possible (but quite improbable) event occurs that the landing of the Apollo vehicle is not known to within about 1,000 nautical miles, then it will be necessary to rely on HF direction-finding techniques. Calculations have already been made to determine the received signal strength from an 8.3 Mcps, 5-watt beacon when the ionosphere is a part of propagating media. These calculations indicate that it is possible to receive signals of adequate level so that slow speed telegraphy is feasible at ranges not exceeding 1,000 nautical miles and not less than about 200 nautical miles.

Others* have estimated the probable accuracy of HF direction-finding bearings to be typically less than 3° for at least 90 per cent of the time. In determining this accuracy, consideration has been given to site errors, observational errors, random sampling errors, and slowly-varying components of lateral deviation. At the maximum range of 1,000 nautical miles, this sort of bearing accuracy would locate the Apollo vehicle to within a circle of about 50-nautical mile radius. The most successful method known for locating the Apollo vehicle within this circle is to use the Sarah beacon system. Figure F-1 (attached) has been extracted from a Mercury memorandum** by R. H. Ellis of this Laboratory. It is shown that the 50-nautical mile search range is easily obtained when the Super Sarah beacon is used. In the same report, suggestions are made for increasing the search range above that indicated in Figure F-1. This improvement in search range is acheived by making some simple modifications to the Sarah receiver located in the search aircraft.

Another system for long-range (1,000 nautical miles or less) position-finding is the Sofar bomb technique. This system is, of course, limited to water landings and in areas where Sofar nets are in operation. Accuracies obtainable with this method are better than those obtained by HF direction-finding systems. In particular, the Sofar bomb system is more reliable because it is not affected by solar disturbances as a system would be that depends on ionospheric propagation.

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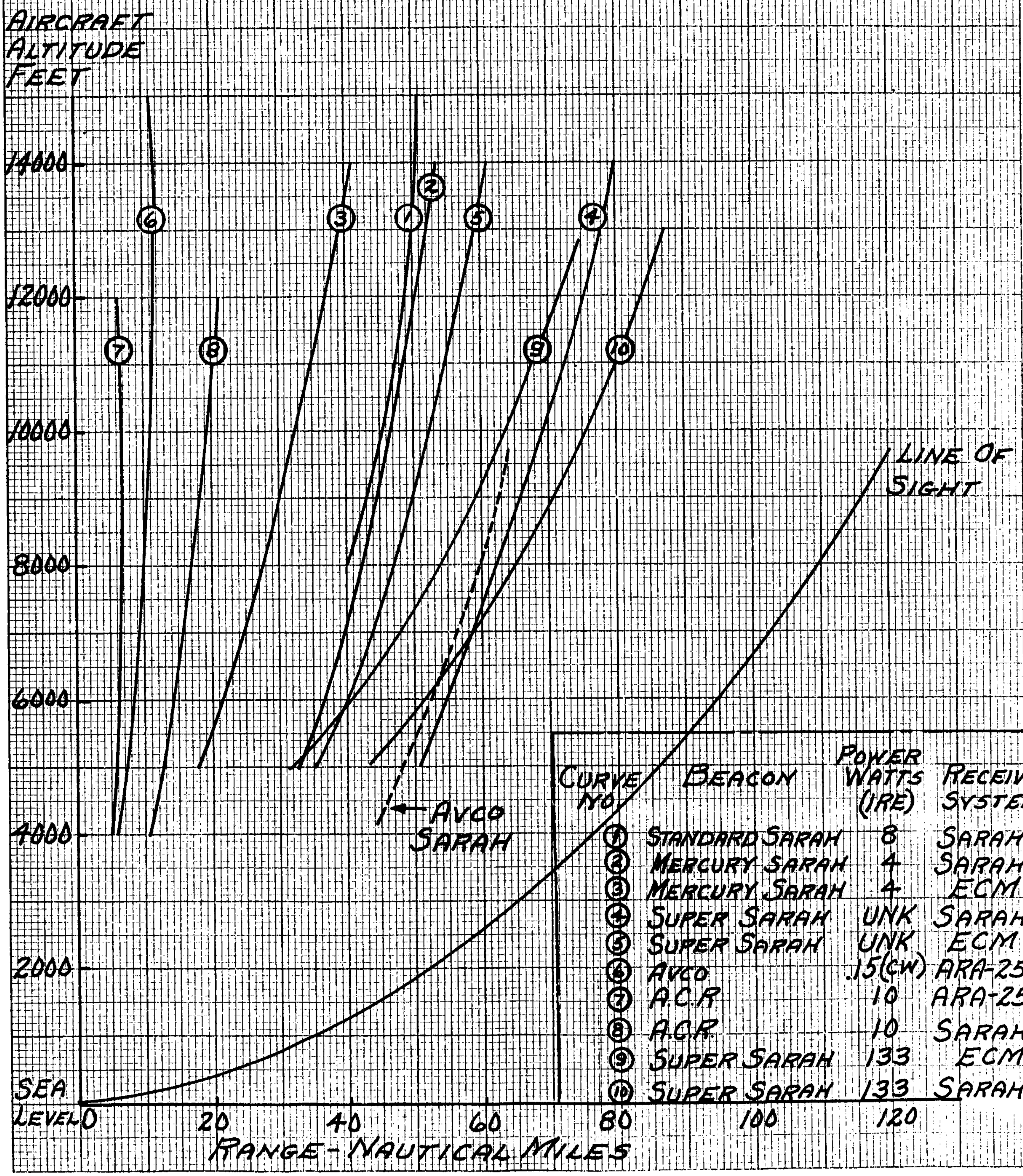
* "The Estimation of Probable Accuracy of High-Frequency Direction-Finding Bearings", Ross, W., Journal I.E.E., 1947, 94, part IIIa, pp. 722-726.

** "Use of the Sarah Beacon in the Recovery Phase of the Mercury Capsule", Ellis, R.H., Lincoln Laboratory Memorandum No. 20-0061

FIGURE #1
COMPARISON OF VARIOUS BEACONS



CURVE NO	BEACON	POWER WATTS (IRE)	RECEIVER SYSTEM
1	STANDARD SARAH	8	SARAH
2	MERCURY SARAH	4	SARAH
3	MERCURY SARAH	4	ECM
4	SUPER SARAH	UNK	SARAH
5	SUPER SARAH	UNK	ECM
6	AVCO	.15 (CW)	ARA-25
7	A.C.R.	10	ARA-25
8	A.C.R.	10	SARAH
9	SUPER SARAH	133	ECM
10	SUPER SARAH	133	SARAH

APPENDIX G

Lunar and Earth Altimeter at 2.2 GC/s

by

R. H. Vacca

Assuming

1. 2.2Gc/s frequency
2. 100 watts peak power
3. 100 microsecond pulse (one pulse detection)
4. 4-foot parabolic antenna
   a. 26.5 db gain (55 per cent effective)
   b. 8° beam width (1/2 power)
5. system noise temperature is 828° K.
   a. 3 db noise figure receiver
      + 1.5 db loss receiver to antenna
      528°K referred to antenna
   b. antenna looks at 300°K
6. on transmission 1.5 db loss between transmitter and antenna
7. lunar radar cross-section at 2,000 nautical miles is 8.45×10^{9} sq. meters where we have assumed a 4 per cent reflectivity.
8. (S/N) ratio at 2,000 nautical miles is 16.2 db
9. on the basis of (S/N) ratio consideration the range accuracy is 212 meters on a one pulse basis
10. with pulse compression using 13-element optimum code, range accuracy is 16 meters

Conclusion:

Altimeter ranging from the lunar or earth surfaces is entirely feasible at 2,000 nautical miles with 100 microsecond pulses of 100 watts peak power. Accuracy at this range is 212 meters. With a 13-element code on the pulse, the accuracy can be increased to 16 meters. The ultimate limitation on accuracy will probably be determined by variations in lunar terrain height except in a vertical descent on a flat plane.

serial timing of two events may, therefore, be more apparent in frequency multiplex than in time multiplex for two systems with the same nominal frequency response and this may be useful in the analysis of experimental results. If performance alone were to be considered, it is second order effects like the latter that might motivate selection.

A combined tracking and communications link, such as the JPL TRAC(E) system, is well-suited for use in the lower bandwidth Apollo modes; i.e., keep-alive and 3 Kc voice. In this system the information signal phase modulates the carrier with a small deviation, leaving about 50 per cent of transmitted energy in the carrier for lock-on purposes. Coherent detection is performed on the signal at the receiver, providing both the tracking carrier for Doppler measurement and the modulating signal. The 3 Kc voice mode would use direct analog modulation after some peak clipping is performed. The clipping provides improved performance by requiring less SNR at the receiver for a given intelligibility than unclipped speech; direct phase modulation is chosen because equipment requirements are modest so that good reliability should be attainable. The keep-alive and voice channels might be used to modulate the carrier simultaneously for a somewhat higher mode performance by using a subcarrier for keep-alive channel, the subcarrier being located outside the voice spectrum. This proposal has the added feature that the modulation system is simple and the voice and telemetry modulation can be dealt with independently. A disadvantage is that the carrier and information powers can not be adjusted independently of one another; i.e., to retain a carrier component for tracking, at most 50 per cent of the power can go into sidebands. Possibly vestigial single sideband or even double sideband-suppressed carrier* modulation should be considered if the energy is desired in the information sidebands, as indicated in the circuit quality charts of Appendix A.

Higher bandwidth modes for vehicle-to-ground present a challenge to the designer. Limited power is available and a variety of information must be transmitted. Frequency multiplex, such as FM/FM is ruled out as mentioned above except, possibly, for providing separation into a few (2 to 5) channels to ease decommutation synchronization problems and reduce the requirements on commutator and analog-to-digital converter

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* "Synchronous Communications", J. P. Costas, Proc. IRE, Vol, 44, pp. 1713-1718, December 1956.

speed. Time multiplexed systems can be roughly separated into analog and discrete systems, as described earlier, and performance within either group is similar. We will use only the terms PAM and PCM to denote these two divisions. A study* has shown that, when using the present telemetry band, a crossover point exists at system accuracies of about 1 - 2 per cent which points to PAM/FM for use at lower accuracies and PCM/FM at higher ones, if bandwidth and signal power are to be conserved. This finding leads Aeronutronic to suggest a combined system, designated PACM/FM, and evaluation of this system is proceeding. While PCM is capable of lower accuracy transmission by using fewer bits, the fidelity of transmission (or quantization noise) does not have a smooth variability as does PAM, the latter depending on the available signal-to-noise ratio for improved accuracy. On the other hand, there is a practical upper limit on the accuracy available in PAM systems that depends on maintaining the linearity of systems in the field. Conventional systems can be maintained to 1 per cent and through the use of special techniques 0.1 per cent and higher have been occasionally reached.

The higher accuracies can be achieved by PCM without any communication system difficulty, although analog-to-digital conversion equipment linearity must be maintained. Besides the flexibility provided by PCM, other advantages are compatibility with data processing equipment, possibility of incorporating error detecting or correcting schemes in the digital transmission, and increasing popularity of PCM for telemetry which will surely promise a variety of equipment available in the future. The voice input is on equal footing with the telemetry signals when using a time multiplexed telemetry system, so PCM voice transmission must be considered for the mixed voice-telemetry modes. Good intelligibility is obtainable with rates of about 20-30 kilobits/second. For a single large bandwidth signal such as TV, special multiplexing equipment (slow scan, etc.) is advisable or else analog transmission using frequency multiplex or a separate carrier should be used.

The multiplexer for the keep-alive and wide-band telemetry should be separate units. The former has modest requirements and must be highly reliable; the latter can be quite sophisticated and, with modular construction,

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* "Telemetry System Study (U) Final Report", Aeronutronic Publication No. U-743, 18 December 1959.

can provide great flexibility with good opportunity for replacement or interchange of defective components. A carefully designed multiplexer can provide a wide range of sampling rate combinations, with some choice of word lengths and format. The design of a multiplexer should be treated as a logical design problem, and not as an attempt to imitate a mechanical commutator.*

The RF modulation technique for the PCM video signal depends partly on the tracking requirements. Probably tracking would best be done separately, in which case FM, PM or PSK are good methods. If PSK is used, with or without injection of some additional carrier, some constraints are necessary to permit carrier acquisition at the receiver in order to provide a means for coherent detection. Differentially coherent detection can be used instead, in which case other constraints apply. A final choice in this area must await further investigation into the various modulation schemes.

Summary

The advantage of phase-lock operation, pulse coding and coherent detection are the major factors that recommend themselves in selecting a modulation method.

Beyond these the major determinant of modulation method is expediency and cleverness in designing equipment.

* A good example of such an approach is seen in D. H. Ellis and J. M. Walter, Jr., "An Analog and Digital Airborne Data Acquisition System", Proc. IRE, Vol. 48, pp. 713-724, April 1960.